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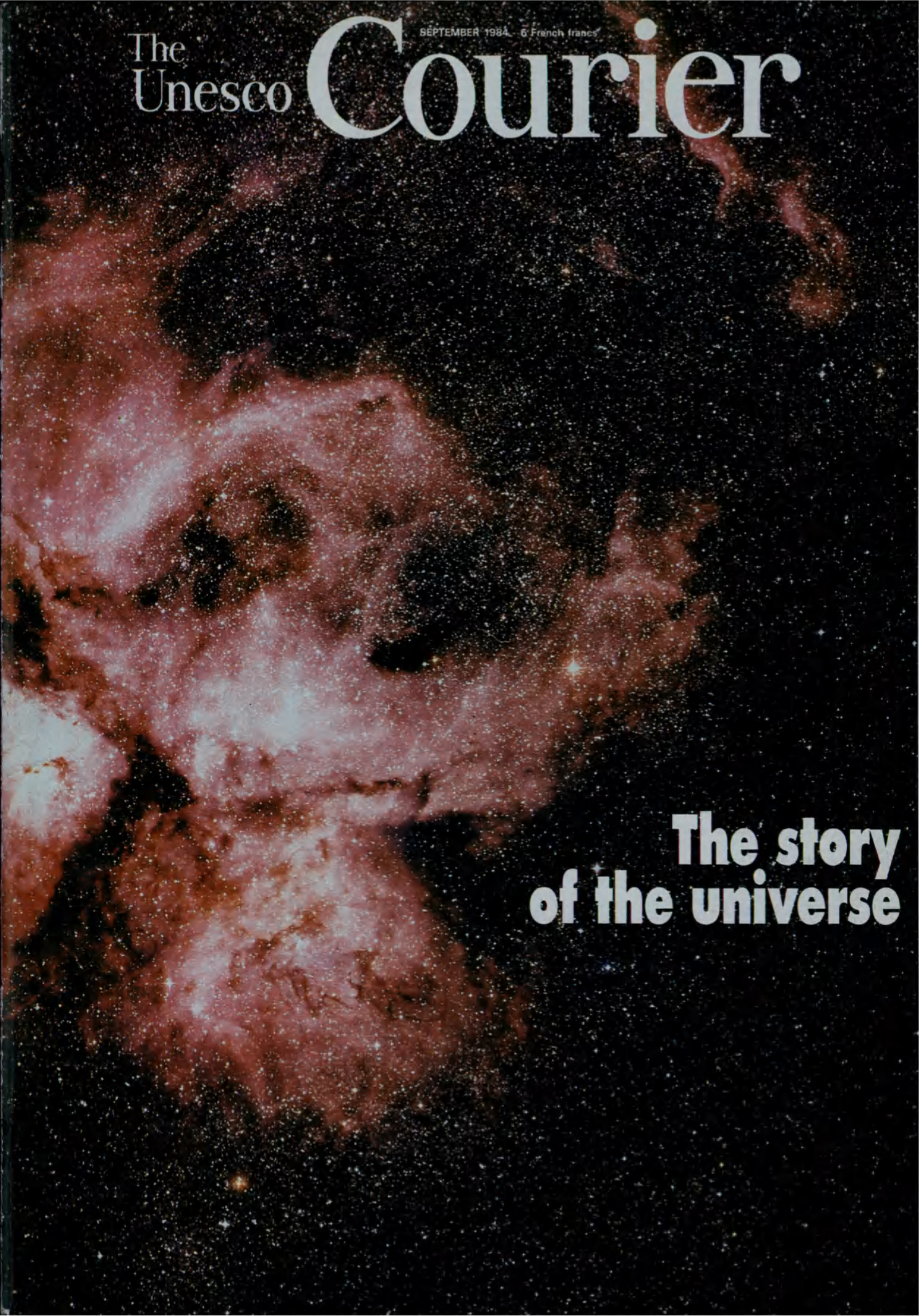
The Unesco Courier



The story of the universe

Photo © IPS, Paris

A time to live...

27 Outer Space

Armchair Icarus

On day five of an historic eight-day space mission which began on 3 February 1984, the dream of Icarus was fulfilled when a man soared alone in space, 280 kilometres above the earth, without even a lifeline to tether him to his mother space-craft. On his twelve-minute maiden flight, the astronaut could rely only on his special backpack, looking for all the world like an armchair that had lost its two front legs. This Manned Manœuvring Unit (MMU), as it is called, is powered by compressed nitrogen thruster jets operated by controls situated on the arms of the "chair". The development of the MMU opens up immense possibilities for a whole new range of activities in space. Already members of a subsequent mission, using MMUs, have succeeded in repairing in space the failing Solar Maximum scientific satellite, giving it a new lease of useful life relaying to earth its observations of the sun.

The Unesco Courier
A window open on the world

Editorial

September 1984
37th year

WITH this special issue of the *Unesco Courier* we offer both an invitation and a challenge to our readers. We invite you all to join us on a voyage of exploration of our Universe, a voyage that ranges from the heart of the atom to the outermost limits of space, from the beginning of time to eternity. We challenge you to give full rein to your imagination as we enter the realm of the unseeable, of the infinitely large and the infinitesimally small.

Isaac Newton, that giant among scientists, was not the first man to see an apple fall to the ground. He was, however, the first to make the daring leap of the imagination which enabled him to see that a falling apple and the Moon circling the Earth were governed by the same force—gravity. Yet when questioned, Newton confessed that, although he knew how gravity behaved, he did not really *understand* how it worked.

So those who find this voyage of discovery difficult to comprehend fully are in good company.

Much of science is concerned with things we cannot see—gravity, sub-atomic particles, light waves, the heart of a star, the galaxies at the outer limits of space. Yet human curiosity about the origins and future of our Universe drives us remorselessly on to probe these mysteries.

In attempting to draw up a balance sheet of where we stand today in this unending quest, to draw a picture of the unseeable, we are obliged to use the language of the everyday "seeable" world. Like the poet, we have to fall back on metaphor and simile. This is why we invite you to bring your imagination with you on this voyage of discovery.

As a teenager in Berne, that other giant scientific genius, Albert Einstein, asked himself "What would the world look like if I rode on a beam of light?". From this innocent but imaginative question sprang the whole of modern physics and the best explanation yet available of the origins of our universe.

Einstein sought explanations but never ceased to marvel at the wonder of the music of the spheres.

For him there was no conflict between the findings of science and the profound cosmological insights of the religions of the world. "The eternally incomprehensible thing about the world", he wrote, "is its comprehensibility".

Come along with us, then as we try to signpost the way towards an understanding of our universe, towards an unending vista of profound delight.

Cover: The Carina Nebula, one of the wonders of the southern sky.

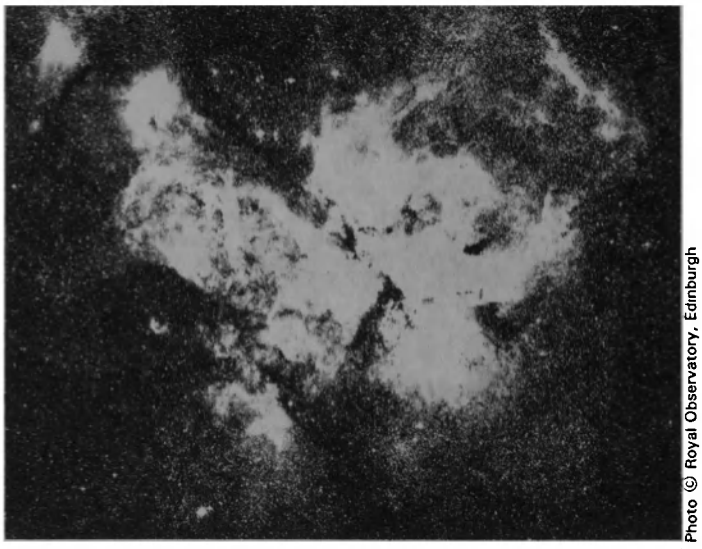


Photo © Royal Observatory, Edinburgh

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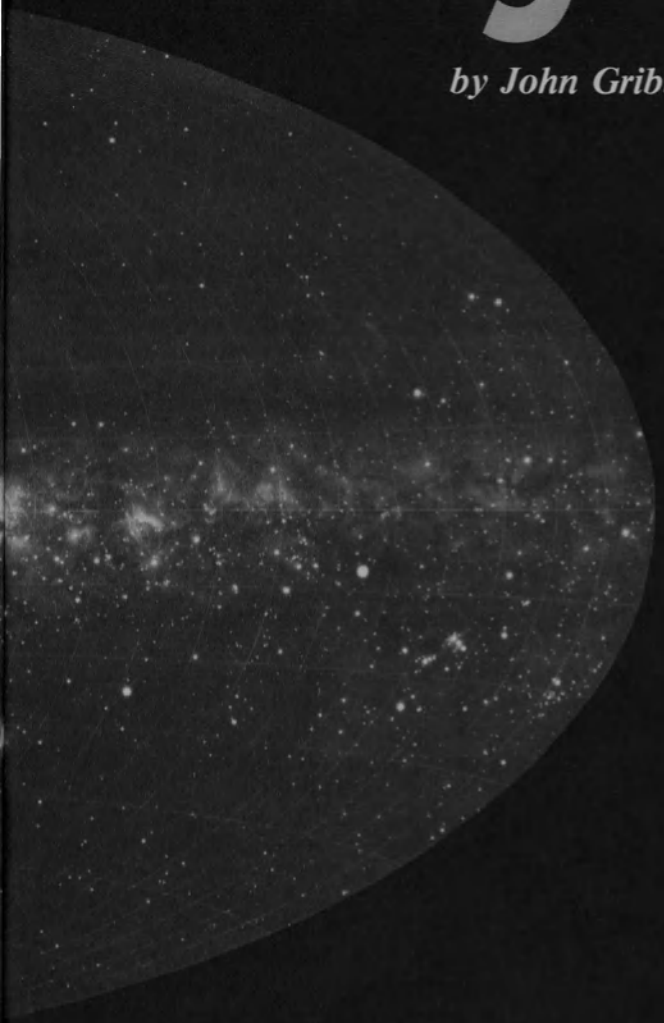
The story of the Universe

The Big Bang

by John Gribbin



The Milky Way

Photomontage of our galaxy viewed edge-on as it would appear to an observer in our solar system.

Photo © Lund Observatory, Sweden

WHERE do we come from? The most fundamental question in all of science concerns the ultimate origin of the Universe in which we live, and it is arguably the greatest achievement of science to be able to answer that question, not yet with complete precision but already sufficiently accurately to satisfy all but the most probing of questioners. The modern picture of the Universe is one of expansion. Clusters of galaxies move apart from one another as the space between them expands, and that can only mean that long ago the galaxies were closer together. The implication is that at a certain time in the past, which can be calculated as roughly 15 thousand million years ago, all of the matter and energy in the Universe was concentrated in a mathematical point, a singularity, from which it burst out to create the Universe as we know it. That outburst has been dubbed "the Big Bang".

The image of the Big Bang Universe is one of change and evolution, yet as recently as the early 1920s astronomers believed the Universe to be constant and unchanging. At that time, it was thought that the stars which make up the Milky Way *were* the Universe, and that although individual stars might be born, live and die, the Milky Way itself continued more or less unchanged, just as a forest may remain more or less unchanged even though individual trees grow, live their lives and die. But this image of stability was shattered in the 1920s by a combination of new developments in both theory and observations.

The theory came from Albert Einstein—it was his General Theory of Relativity, published in 1917. General Relativity describes the nature of gravity, and the Universe at large is dominated by gravity. In terms of Einstein's equations, gravity is thought of as bending space (more accurately, space-time), and the amount of matter there is in the Universe determines the extent to which space is curved. In Einstein's view of the Universe, empty space, or space-time, is something that has a dynamic life of its own, bending, expanding or contracting in accordance with well-defined laws. Einstein, like all his contemporaries, believed that the Universe was static and unchanging. He was horrified to discover that his equations predicted that space-time ought to be expanding—that the Universe should be getting bigger—and he "corrected" the equations by introducing a new term, a "cosmological constant", to cancel out the expansion and restore stability. In later years, he described this as the biggest scientific mistake he ever made.

In the early 1920s, Einstein's equations describing the nature of the Universe were refined by the Russian Alexander Friedmann, who produced the standard set of solutions to the equations in 1922. The Friedmann Models, as they are called, provide two basic possibilities which remain the basis for our understanding of the Universe today. Both versions start from a singularity—a state of infinite density—and expand away into states of lesser density. But space is curved according to the amount of matter in the Universe, which leads to two alternatives. If there is less than a critical amount of matter, the expansion must continue forever, with galaxy clusters moving ever further apart. In that case, the Universe is "open". But if there is more matter than the critical amount, then gravity is strong enough to curve space so much that the expansion is first halted and then turned into a collapse, so that the Universe falls back into a superdense state. Such a Universe is called "closed". ▶

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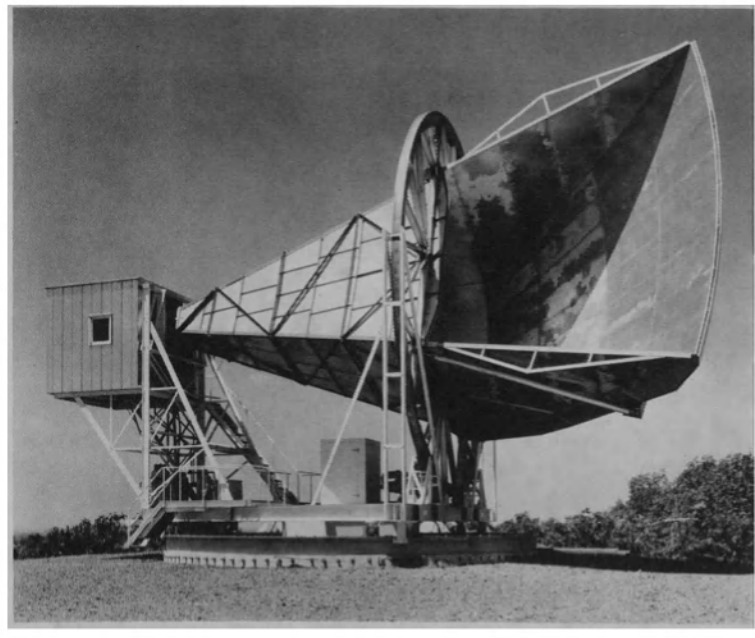
The echo of the Big Bang

It has been hailed as the most remarkable scientific observation of modern times, and like many great discoveries it came about by accident. In 1964 radio-astronomers Arno Penzias and Robert Wilson of the Bell Telephone Laboratories in the United States detected a baffling radio noise through the giant "ear trumpet", a 7-metre horn antenna (right) with which they were working on the development of a satellite communication system. The noise seemed to come evenly from all directions in the sky. It did not change as the months went by and, with the rotation of the earth around its own axis and around the sun, the antenna was pointed to different parts of the sky. It could not be accounted for by any source on earth, in the solar system, or in our galaxy. Could it be due to a fault in their equipment? Could it be caused by the pigeons roosting in the throat of the antenna? The antenna was dismantled and rebuilt, the pigeons were removed. But the noise in their microwave receiver was still, inexplicably, there.

Then Penzias and Wilson heard about the calculations of a Princeton University physicist, P.J.E. Peebles, who had calculated that if the universe had originated in a Big Bang, a massive amount of radiation would have been needed to prevent all the densely packed particles from fusing together into heavy elements and to leave enough hydrogen and helium to form the stars and galaxies of the universe as we know them today. As the universe expanded, the radiation cooled, continuing to permeate the universe but in a weaker, more "diluted" form. Peebles predicted that it should today be detectable as radiation with a temperature of a few degrees above absolute zero on the Kelvin scale. This immediately explained the origin of the radio hiss heard by Penzias and Wilson: this cosmic radiation filling all of space was a distant echo of the Big Bang. The



excitement of astronomers at the discovery of a phenomenon which seemed to confirm the Big Bang theory so conclusively was mingled with the irony that radio telescopes of the 1950s would have been capable of detecting this background radiation, whose existence had been predicted in the mid-1940s, but no radio astronomers had looked for it. In 1978 Penzias and Wilson were awarded the Nobel Prize for their discovery.

▶ Just at the time these new theoretical ideas were emerging, astronomers were developing a series of large telescopes which probed the nature of the Universe and showed how parochial their earlier ideas had been. Our Milky Way Galaxy, the mass of all the stars visible in the night sky, was shown to be just one collection of stars among many in the Universe. The Milky Way contains thousands of millions of stars, a collection forming a flattened disc like an island in space, but the Universe contains many millions of other galaxies like this, separated from one another by truly empty stretches of intergalactic space. The crucial discoveries concerning the nature of these objects came from a succession of telescopes on mountain tops in California—the 60-inch reflector at Mount Wilson, completed in 1908; the 100-inch at the same observatory in 1917; the 200-inch at Mount Palomar in 1948. Edwin Hubble, working at the Mount Wilson observatory from 1919 onward, first showed that many faint patches of light in the sky could be resolved into individual stars, and were island galaxies in their own right, lying far beyond the Milky Way. He then made an even more dramatic discovery. He found that distant galaxies show a systematic red shift in their light, a red shift that is proportional to the distance of each galaxy from us.

This red shift literally involves a displacement of features in the visible spectrum from their expected position towards the red end of the spectrum. It is interpreted as a stretching of the light waves, because red light is at the long wave end of the visible spectrum (blue light has shorter wavelengths; a compression of wavelengths would cause a blue shift). There is only one plausible explanation for such a phenomenon. The wavelength of the light is stretched because the distant galaxy is moving away from us, in exactly the same way that the note of a police or ambulance siren is deepened if the vehicle rushes away from us. Hubble's discovery in the 1920s that red shift is proportional to distance was exactly the effect predicted by the Einstein/Friedmann models, the effect Einstein tried to get rid of with his cosmological constant. It doesn't mean that our Galaxy is at a special place at the centre of the Universe, with everything else moving out from it, because those distant galaxies will "see" *us* in retreat from *them*. The motion is relative. Imagine an expanding balloon, dotted with paint spots and being inflated. Every spot "sees" every other spot receding at a rate proportional to the separation of the two spots, but none of the spots is actually moving across the rubber of the balloon's skin (See page 16). Hubble's law showed that the Universe is made the same way—empty space, Einstein's space-time, expands and pushes the galaxies further apart, even though the galaxies themselves are not moving through space.

Astronomers were intellectually aware of this in the 1930s, and for three decades they lived with the implication that the Universe must have had a definite beginning from which the universal expansion had begun. But it was only in the 1960s that this abstract intellectual concept became something more concrete and immediate. The Big Bang was an abstract concept, seemingly remote from the world of today. It couldn't be seen, or felt, or touched, and astronomers seem to have had no "gut feeling" that the idea was correct. And then, in 1964 Arno Penzias and Robert Wilson, working at the Bell Laboratories in the US, found a way to "touch" the Big Bang.

Penzias and Wilson had been working with a sensitive radio antenna and amplifier system studying faint radio signals bounced off the Echo satellites. They also took the

opportunity to use this sensitive equipment to study the faint radio noise of the Milky Way, and to their surprise they found a weak, but uniform, signal coming from all directions in space. Space—the Universe—seemed to be full of very weak radio waves, with an energy equivalent to 3 K (zero on the Kelvin scale of temperature is −273 °C). This is a very weak signal by everyday standards, but if it fills all of space it adds up to a great deal of energy altogether. Where had it come from? Princeton theorist P.J.E. Peebles, working just a few miles away from Penzias and Wilson, quickly came up with the answer. This weak, 3 K background radiation must be the echo of the Big Bang itself, the last trace of the fireball in which the Universe was born.

The argument is simple. When the Universe was born out of the Big Bang, it was very hot, full of energy as well as matter. As space expanded, the radiation expanded as well, so that space has always been full of this electromagnetic energy. But as space has got bigger, the energy has been more and more diluted. The density of the energy has got less, and so its temperature has fallen. The temperature of the background radiation today is exactly right for the amount of expansion that must have occurred since the Big Bang, and there is no serious alternative explanation for the discovery made by Penzias and Wilson. Following that discovery, astronomers had to accept, deep down in their hearts, that the Big Bang was real, not just some interesting quirk of the mathematical equations. Penzias and Wilson received the Nobel Prize for their discovery in 1978, some measure of the impact it made on science.

The discovery of the cosmic background radiation led to new interest in the Big Bang. How, astronomers wanted to know, could a superdense, superhot fireball of energy have expanded and evolved into the Universe we see about us, where stars are gathered into galaxies which move quietly apart from one another in an expanding sea of space-time? The universal expansion has long since been proved a reality; we can take the temperature of the Big Bang itself, and we know that the origin of the Universe lies in a fireball of creation 15 thousand million years ago. Those were dramatic discoveries in themselves to previous generations. But in the past ten years even more dramatic progress has been made, not by astronomers but by particle physicists whose work with giant accelerators like those at CERN (the European Organization for Nuclear Research) in Geneva has given them an insight into the world of very high energies. We cannot, in fact, go back to the instant of creation, when the Universe was infinitely dense and infinitely energetic, and occupied a mathematical point with zero volume. But the theorists can come pretty close to this. They now claim to have pushed back the understanding of the Big Bang to the point where they can explain how a minuscule object, a Universe containing all the mass energy of our present Universe packed into the volume of a proton, blew up into something like the Universe we see today.

■ **John Gribbin**

Photo © Bell Telephone Laboratories, USA, and *Sciences et Avenir*, Paris

"Shorthand" for mathematicians

Any discussion of the universe and of particle physics involves talking about both very large and very small distances and quantities. We therefore need a form of shorthand to express the very large numbers involved. Conventionally, for example, ten times ten times ten—i.e. one thousand—is expressed as 10^3, one million is written as 10^6, and 10^{14} means a hundred million million. A similar method is used to express very small distances or quantities; one divided by a million—i.e. one-millionth—is expressed as 10^{-6}. The radius of an atom, for example, is about 10^{-8} of a centimetre.

Open or closed? The fate of the Universe

If we accept, as do most physicists today (for alternative view see article page 13), that the universe began with the "Big Bang" and is expanding, is it possible to deduce how it will end? There seem to be two possible scenarios for the future and the choice between them is finely balanced. Everything hinges on just how much matter there is in the universe. Just as our solar system and all the galaxies are held together by the attractive force of gravity, so the total mass of the universe exercises a steady pull on all its components. As the universe expands, impelled by the explosive force of the Big Bang, this gravitational pull decreases. But if there is enough matter in the universe, gravity will eventually overcome the expansion which will gradually slow to a halt. Like a film being run backwards, the whole process will go into reverse, the universe will contract faster and faster as the force of gravity becomes increasingly ascendant until it collapses back into another dense fireball, perhaps to die for ever, perhaps to expand again in another Big Bang. If, however, the total mass of the universe is insufficient to enable the gravitational force to become predominant, the expansion of the universe will continue for ever. Cosmologists have attempted to work out the total mass of the universe by measuring the amount of matter in the volume of space that we can "see". Curiously, their estimates give an approximate total mass for the universe that lies within the critical zone between these two possibilities. The fate of the universe is balanced on a knife edge.

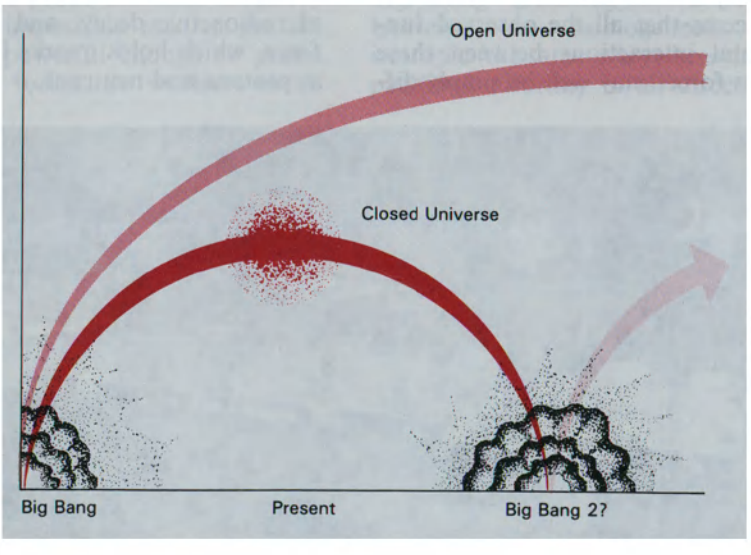


Diagram Unesco Courier

Photo © Observatoire de Paris

***Spiral nebula (M81), in* Ursa Major.**

The infinitely big

by Dimitri V. Nanopoulos

UP to a few years ago, particle physicists were mainly concerned with the structure of matter and the fundamental laws of nature at very small distances of the order of 0.0000000000001 centimetres (10^{-13}) or smaller. At the same time, astronomers and astrophysicists were trying to understand the large-scale structure of the Universe which involved thinking in terms of distances measured in light-years (the distance that light, which travels at 300,000 kilometres per second, traverses in one year). It is fair to say that the relations between these two active branches of physics were rather remote.

During the past few years, however, the situation has changed dramatically; the "Big Bang" theory of the origin of the Universe (see article page 5) has developed to the point where the first fractions of a second of the birth of the Universe have become the meeting point of the infinitely big and the infinitesimally small*.

In order to appreciate this point we have to recall two fundamental principles of physics: first, that high temperatures imply high energies for the particles around; and second, according to the "Uncertainty Principle" formulated by the famous German physicist Werner Karl Heisenberg (1901-1976) high energies are necessary to probe very small distances.

According to the Big Bang theory, the very early Universe (say 10^{-35} of a second after the Big Bang occurred) was very hot, reaching temperatures above 10^{28} degrees on the Kelvin (K) scale. At these temperatures particles had enough energy to interact at very very small distances, say 10^{-29} centimetres. Thus the very early Universe acted like an enormous particle accelerator. Today, the fundamental constituents of matter are believed to be quarks and leptons. Atoms, which at one time were thought to be indivisible, are made up of protons and neutrons (known collectively as baryons) and one member of the lepton family, the electron; protons and neutrons are made up of quarks.

These fundamental constituents of matter interact with each other through at least four fundamental forces: the *gravitational force,* which, for instance, keeps the Earth going round the Sun, the *strong force,* which keeps quarks inside protons, the *electromagnetic force,* that keeps the electron going round the atomic nucleus, and the *weak force,* responsible for neutron disintegration, otherwise known as Beta-decay.

During the past few years, the world of particle physics has enjoyed enormous progress towards simplification and deeper understanding. Indeed, it now seems that all the observed fundamental interactions between these various forces may well be simply different faces of a single basic interaction explicable by a basic unified theory.

Because we live in a Universe of large distances (or low energy levels) it is difficult for us to recognize this basic symmetry at first glance; things look very diverse. Yet as we examine shorter and shorter distances (or higher and higher energy levels), the diversity diminishes and the symmetry becomes more apparent. The analogy of ice, water and steam may help here. As we increase the temperature and pass from ice to water, particles possess more and more freedom to move around and thus the system increases its symmetry, which is further increased when we pass from water to steam.

The idea of unification is not new. Einstein himself spent the last thirty years of his life unsuccessfully attempting to formulate a simple, definitive theory that would explain the existence of all matter, all energy and all the forces of the Universe. Right up to his death, in 1955, Einstein continued working to establish unity between the forces of gravity and of electromagnetism.

It was, however, in the small-scale realm of sub-atomic particles that the next advance towards unification was to be made. This is a world ruled by the *weak force,* which causes certain forms of radioactive decay, and the *strong force,* which holds quarks imprisoned in protons and neutrons.

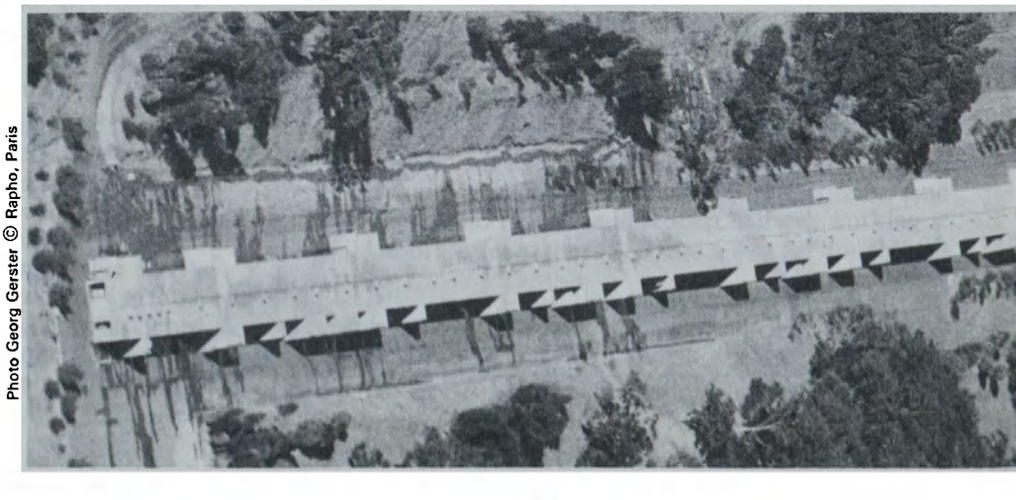


Photo Georg Gerster © Rapho, Paris

** The layman tends to picture the Big Bang in terms of a very dense lump of matter (which scientists call a "singularity"), located in an infinite void, suddenly exploding. Einstein, however, has shown that both space and time (which he called space-time) and matter were inseparable. The Big Bang, therefore, created not just matter but space-time as well. There was nothing, not even empty space, "outside" for the Big Bang to explode into.*

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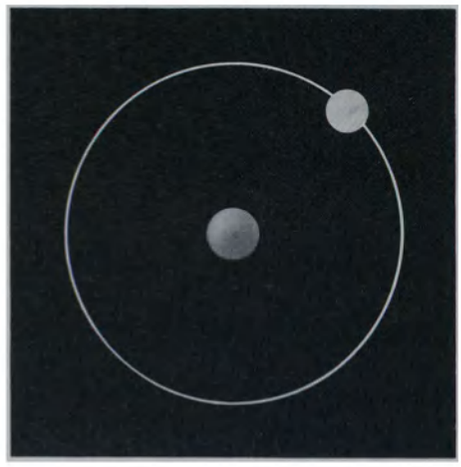
and the infinitesimally small



A hydrogen atom

The first step, the unification between electromagnetic and weak interactions, was first envisaged theoretically in the 1960s and then proven experimentally, only last year, in the giant accelerator at CERN (The European Organization for Nuclear Research), in Geneva, with the discovery of particles, named simply W and Z particles, that carry the weak force.

Because of similarities between the mathematical formulae describing the strong and the weak forces, physicists began to suspect that they might both be breakaways from a single unified force that existed at the very earliest phase of the Big Bang.

The next step in the unification programme therefore would be to explain how the strong force fits into the picture, and this is what is being attempted in current theories known as "Grand Unified Theories" (GUTs). The final stage in the unification programme will be to include gravity, but this need not concern us here.

According to Grand Unified Theories, the strong forces should unite with weak forces at enormously higher energies, around 10^{24} electron volts. But although we now have at our disposal particle accelerators which enable us to probe the weak forces, it would be impossible ever to get accelerators powerful enough to probe the strong forces. So we have to be smarter and look for indirect evidence for grand unification.

Certain characteristics of GUTs are very relevant to the early universe. One of the most dramatic consequences of GUTs is that they imply the instability of matter. Whereas, prior to the development of GUTs, protons, and thus atoms and thus matter, were considered to be absolutely stable, GUT interactions imply the decay of the proton, just as weak interactions cause the decay of the neutron. Eventually, it seems, all the matter in the Universe as we know it will be destroyed.

However, while the free neutron lifetime is about fifteen minutes, the proton lifetime is longer than 10^{30} years which is long enough to avoid immediate panic if we recall that the present age of the universe is merely 10^{10} years. For the first time "eternity" has been given a quantitative measure of the order of 10^{30} years. Experiments are now being made to verify this formidable GUT consequence.

What has all this intricate detail about the world of sub-atomic particles to do with cosmology? There is enough experimental evidence to convince us that standard Big Bang cosmological theory may reflect something close to reality. Nevertheless, there are fundamental unanswered questions within Big Bang cosmology. Why is the Universe so homogeneous and isotropic (the same everywhere and expanding uniformly in all directions)? Why does the Universe, despite its rather old age (10^{10} years), possess such high mean energy density? Why is it that there seems to exist much more matter than anti-matter? How are the density fluctuations created that eventually act as seeds for the formation of galaxies and other structures observed in the Universe? A lot of these questions are finding satisfactory answers in grand unified theories.

In the first fiery instant of the Big Bang the Universe was superhot and superdense and a single unified force prevailed. But, as it was expanding, it cooled down and became less and less dense, and, in a process called "symmetry breaking", the single unified force began to fragment.

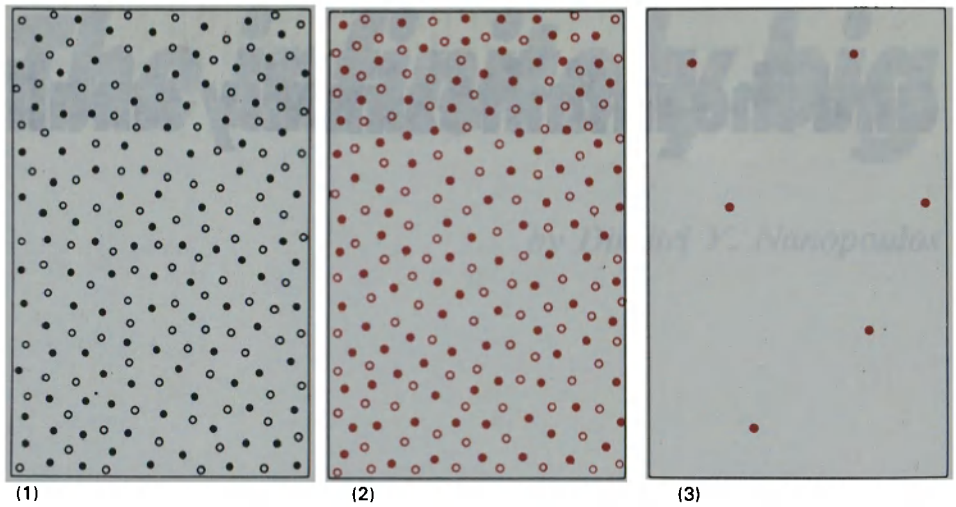
It is reasonable to assume that, after the Big Bang, all kinds of particles were interacting frenetically with each other in a state of what is called thermal equilibrium. Given this "soup" of particles, and assuming that grand unified theories correctly describe their interactions, can we build up a picture which corresponds to the observable Universe? The answer is a cautious yes.

As the Universe expanded and cooled further it eventually reached what physicists call the GUT transition phase where the strong and weak forces ▶

The principal tool used by physicists to probe the secrets of the world of the infinitesimally small is the particle accelerator, or "atom smasher". Atom smashers are huge machines in which atomic particles are accelerated to fantastic speeds and made to collide with other particles so that physicists can examine the resulting sub-atomic debris. It was in the atom smasher at CERN (the European Organization for Atomic Research), in Geneva, until last year the world's most powerful accelerator in which beams of protons and anti-protons can be made to collide with a total energy of 540 thousand million volts, that the W and Z particles which carry the weak force (see article) were recently discovered. Left, aerial view of the 3,050-metre-long linear particle accelerator at Stanford, California.

Cosmic asymmetry

The fundamental constituents of matter come in matched pairs. For every particle there is an anti-particle of identical mass but with a different electrical charge. This symmetry between particles and anti-particles, which meets the requirements of both the theory of relativity and of quantum physics, has been fully verified experimentally. High-energy collisions induced in particle accelerators seem always to yield particles and anti-particles (matter and anti-matter) in equal quantities. When we move away from the laboratory, however, we never seem to encounter anti-matter. Our world is made of atoms consisting of protons, neutrons and electrons, but never of their anti-particles. Recent findings in cosmology and particle physics, which have given rise to the new Grand Unified Theories (see article), offer an explanation of how this asymmetry between matter and anti-matter came about. Above, diagram (1) represents the universe at 10^{-35} of a second after the Big Bang. At this stage there is symmetry between the superheavy "X" particles (black dots) produced by ultra-high energy collisions, and their anti-particles (black circles). Diagram (2) shows the universe from 10^{-34} to 10^{-4} of a second after the Big Bang. Here the "X" particles have decayed into less massive particles in a manner that results in a minute imbalance between protons (red dots) and anti-protons (red circles). Diagram (3) represents the universe from 10^{-3} of a second after the Big Bang to the present. Each encounter of a proton and an anti-proton has led to the annihilation of both and only the excess protons (one per thousand million) remain. To this minute imbalance we owe all the galaxies, stars, planets and creatures of the universe.



(1) (2) (3)

Diagrams Gabor Kiss © Scientific American, New York

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▶split and grand unification was no longer apparent. This happened when the Universe was about 10^{-35} of a second old and had a temperature of 10^{28}K.

This is a period of fundamental cosmological importance since during this transition phase—a period of supercooling—the Universe experienced a brief, hyper-explosive spurt of exponential growth, a period in which the Universe expanded at a very much faster rate than during any other phase. The advantage of this "inflationary scenario" as it is called is that this sudden, brief period of extremely rapid expansion of the Universe provides a solution to the problem of how parts of the Universe, which would otherwise have been too far apart to be in causal contact with each other come to have similar temperatures. Our large Universe is very uniform because it has been inflated from a tiny uniform seed. The inflationary model solves the problem of the high average energy density of the Universe as well as providing the correct form, qualitatively and quantitatively, of the energy density perturbations needed for galaxy formation.

The inflationary model also provides the answer to another crucial problem. How is it that more matter than anti-matter was produced from the Big Bang?

Grand unified theories predict the existence at the very high temperatures of the very early phases of the Big Bang of superheavy "X particles" which decay into less massive particles and, in so doing can produce an unequal mixture of matter (baryons) and anti-matter (anti-baryons). At a time just 10^{-35} seconds after the Big Bang the temperature had fallen to a level at which no further X particles could be made and a slight asymmetry (one unpaired baryon per thousand million baryon/anti-baryon pairs) was locked forever into the expanding Universe. This small excess of matter over anti-matter—the afterthought of creation—was sufficient to produce all the stars in all the galaxies and all the atoms in our own bodies. It is rather interesting that the same forces that are responsible for the creation of the world (matter/anti-matter asymmetry) are driving it to its extinction (proton decay and thus matter instability). That is the fate of our Universe—self-destruction.

Eventually the Universe left the GUT transition phase and began to expand and cool down at a slower, more conventional rate.

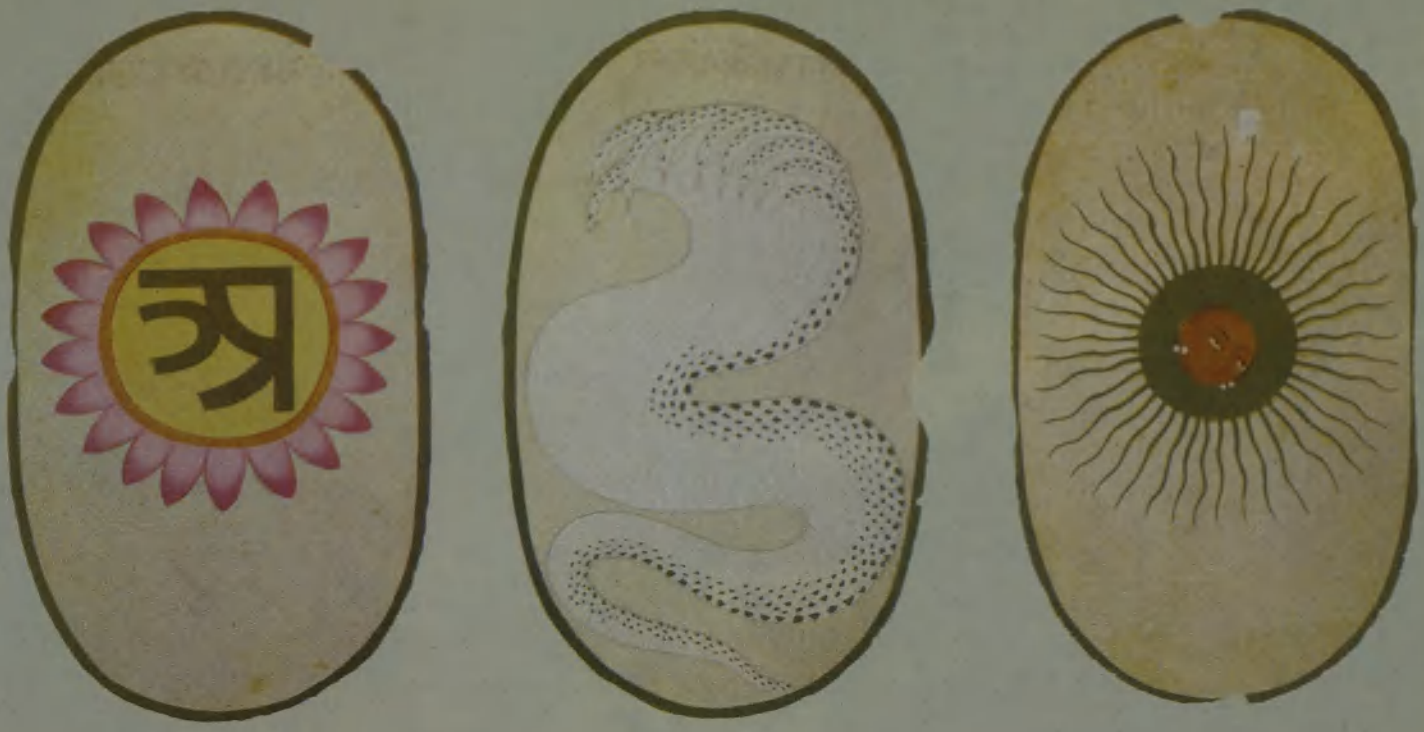
At this stage the particle physicists step aside, leaving it to the astrophysicists to tell the story of how heavy elements, stars, planets and galaxies are made. Nevertheless, in journeying further and further back towards the Big Bang and probing more deeply into the world of the infinitesimally small, particle physicists are offering astrophysicists a basis for a logical, coherent explanation of the structure of the Universe. Never before in the history of physics has the symbiosis between the infinitesimally small (the microcosmos) and the infinitely big (the macrocosmos) been happier or more fruitful.

■ **Dimitri V. Nanopoulos**

Colour page 11

Explanations of varying degrees of complexity of the origin and nature of the universe are found in almost all cultures. Many of them see the origin of the universe as a process involving the bringing of order to a primeval chaos, while others refer to the spontaneous hatching of the "cosmic egg". Above, three Tantric paintings from Kangra, in the State of Himachal Pradesh, northwestern India. Left, representation of the sacred syllable OM, considered the greatest of all the mantras (sacred phrases imbued with mystic power). It is composed of the three sounds, a-u-m, that vibrated at the beginning of the Creation. The three sounds represent the three worlds (earth, atmosphere, heaven), three Hindu gods (Brahma, Vishnu, Siva) and the three sacred Vedic texts (Rg, Yajur, Sama) and thus embody the essence of the entire universe. Centre, the power of the serpent Anantanag symbolizes the original cosmic energy which creates, sustains and destroys the entire structure of the universe. Right, the cosmic sun which gives birth, by the power of its rays, to the phenomenal world. Below, detail from an ancient Egyptian papyrus (XXIst Dynasty, 1085-945 BC) depicts the reclining figure of Geb, god of the earth, beneath the vault of heaven, as represented by the arched body of Nut, goddess of the sky.

Photo © Réunion des Musées Nationaux, Paris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Was there really a BIG BANG?

by Jayant V. Narlikar

WHAT do we know about the origin of the Universe? If today an opinion poll were to be conducted on this question, a great majority of astronomers would agree with the view that the Universe came into existence in a gigantic explosion that took place some 10 to 15 thousand million years ago.

This conventional view, commonly known as the "Big Bang" theory, has it that at the moment of origin the Universe was infinitely dense and infinitely hot but as it expanded in all directions, it cooled and became less dense. Soon after the Big Bang, there formed from its debris the basic building blocks of matter which later developed into large astronomical units that we recognize today as stars, galaxies, clusters of galaxies and so on.

Although the Universe is still expanding as a result of that initial Big Bang and all the galaxies are moving away from one another, the ferocity of the initial explosion is no longer present now, nor is the universe very hot or very dense. Its overall temperature is estimated at about 270 degrees Celsius (Centigrade) below zero, while an average cubic volume of a million kilometre size is believed to contain no more than about one kilogram of visible matter.

Cosmology is the branch of science concerned with the study of the large scale structure of the Universe, its origin and its evolution. Like other parts of astronomy (and of science in general) cosmology has its share of controversies and, if history is any guide, the majority view has not always prevailed. For, in the last analysis speculations, however popular, have to give way before hard facts.

The Big Bang scenario described above has grown over the years out of a series of plausible speculations based on a comparatively few hard facts. But do we have the guarantee that in this scenario we have at last found the answer to the ultimate question that man has been attempting to grapple with since time immemorial? Have we reached the level of sophistication needed to understand the origin of the Universe?

Opinions differ amongst scientists on this question. There are those who feel that with the unification of all the basic forces of nature in sight, the "end of physics" is not too far away. For them the cosmological problem is also near its solution. I share the more pessimistic (and more realistic?) assessment of English astronomer Sir Fred Hoyle who said in 1970:

"I think it is very unlikely that a creature evolving on this planet, the human being, is likely to possess a brain that is fully capable of understanding physics in its totality. I think this is inherently improbable in the first place, but, even if it should be so, it is surely wildly improbable that this situation should just have been reached in the year 1970".

With these reservations in mind one can ask if the presently popular Big Bang scenario is the only plausible one for the origin and evolution of the Universe.

The discovery that the Universe is expanding was made by the American astronomer Edwin Hubble (1889-1953) in 1929. Hubble's original observations have since been repeated with greater accuracy and out to greater distances, and these have confirmed the view that the space in which the galaxies are embedded is expanding. The rate of expansion of the Universe at any given epoch is measured by a constant H, commonly known as Hubble's constant.

Given the fact that the Universe is presently expanding we need a dynamic theory to tell us what it did in the past and what it will do in the future. Einstein's General Theory of Relativity is the simplest and most suitable theory available today for this purpose. Models of the Universe based on this theory lead us to the concept of the Big Bang origin. According to these models the density of the Universe and the Hubble rate of expansion would be found to be higher and higher as we probe the history of the Universe further back in time, so much so that at an epoch a finite time ago both these quantities were infinite. This is the Big Bang epoch. ▶

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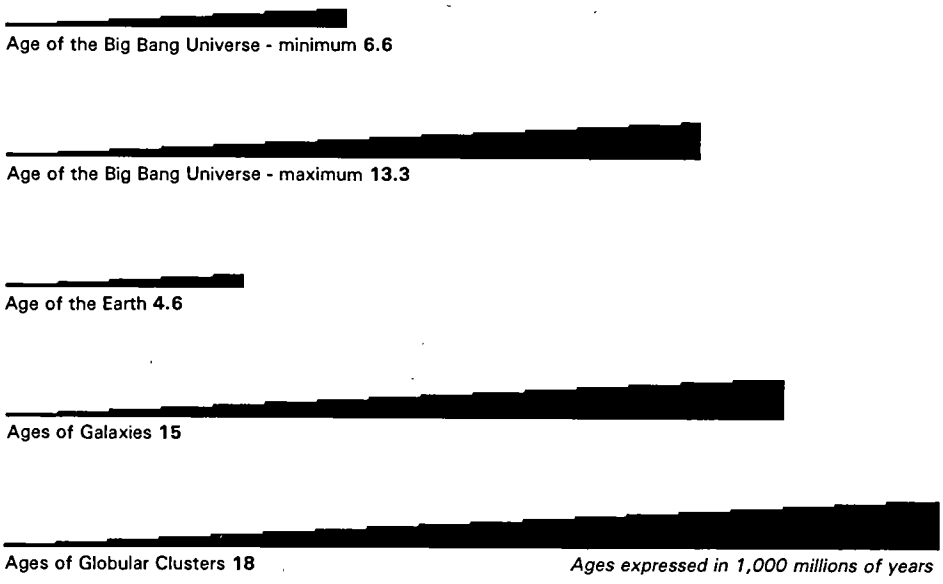
Colour page 12

The !Kung Bushmen of the Kalahari Desert in Botswana call the Milky Way, which is often overhead at their latitude, "the backbone of night". They believe that the Galaxy holds up the night, as if the sky were a great beast within which we live. Jon Lomberg's painting* The Backbone of Night *is inspired by this metaphor about the Milky Way.

Photo © Jon Lomberg, Toronto, Canada


Age of the Big Bang Universe - minimum 6.6
Age of the Big Bang Universe - maximum 13.3
Age of the Earth 4.6
Ages of Galaxies 15
Ages of Globular Clusters 18
Ages expressed in 1,000 millions of years

Because of the present uncertainties in the value of Hubble's constant, the age of the Big Bang universe is believed to lie between 6,600 million and 13,300 million years. This age range can accommodate the age of the earth but not of the older galaxies or globular clusters.

▶ Physicists normally become suspicious of the validity of their theoretical framework if it leads them to infinities like this. Einstein's theory makes the situation even worse because it links the density and the motion of matter with the geometrical properties of space and time. At the Big Bang epoch, therefore, it is impossible to define these properties. This total breakdown of physical and mathematical descriptions has led to the Big Bang epoch being called a "singular" epoch.

The appearance of this singularity is more a reflection on the incompleteness of our understanding than a description of physical reality.

The singular epoch is identified with the origin of the Universe. The law of conservation of matter and energy breaks down at this epoch since all the matter (and radiation) present in the Universe would have to be created at this time.

Cosmologists define the age of the Universe as the time elapsed since this epoch and this has been worked out by using the reciprocal of Hubble's constant (in other words by "working the sums out backwards") to calculate how long it would take for the Universe as it is now to *contract* back to the time of the Big Bang.

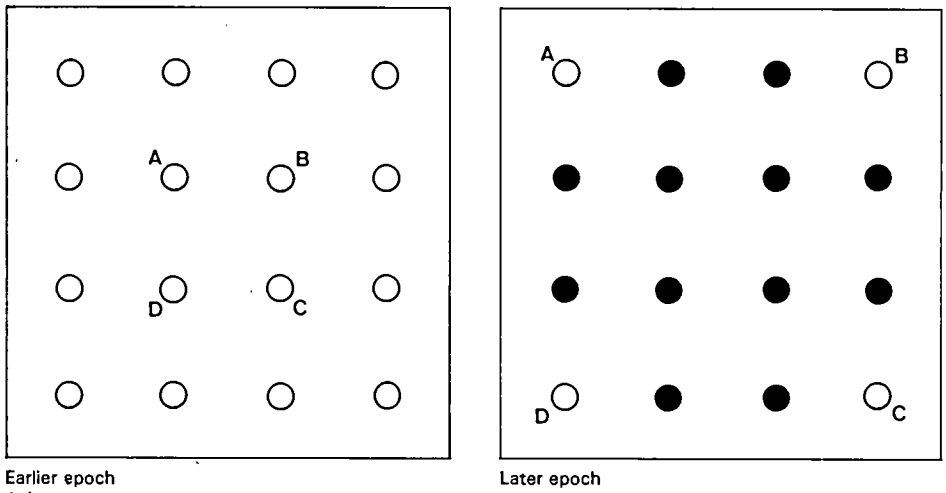
Although astronomical observations today cannot give the value of Hubble's constant accurately, the model universe currently most favoured by cosmologists and particle physicists working together gives an *upper limit* for the time elapsed since the Big Bang of between twenty thousand million and ten thousand million years.

These calculations are based on an idealized model of an empty universe. The presence of matter, however, tends to slow down the expansion of the model universe and to reduce its age. If there is enough matter in the real Universe to slow down its expansion to a momentary standstill followed by contraction (as the most widely accepted version of the Big Bang theory predicts), then its present age cannot be more than two-thirds of the theoretical calculation of the time elapsed since the Big Bang. In other words, the age of the Universe must be somewhere within the range of 13.3 to 6.6 thousand million years.

Large though this age is by human standards, it is not so large in the astronomical context. The age of the Earth is 4.6 thousand million years. The age of our Milky Way Galaxy is variously estimated at 10 to 15 thousand million years. The ages of certain large clusters of stars, called the globular clusters, are even higher, at 17 to 18 thousand million years. It therefore seems that if all matter were created in the Big Bang it is simply impossible to accommodate most of these astronomical systems within the time span available.

It is clear that these problems arise because of the so called "origin" of the Universe. Are there models of the Universe *without* an origin, models in which the Universe is infinitely old? For such models one has to go beyond the more conservative framework of Einstein's general relativity.

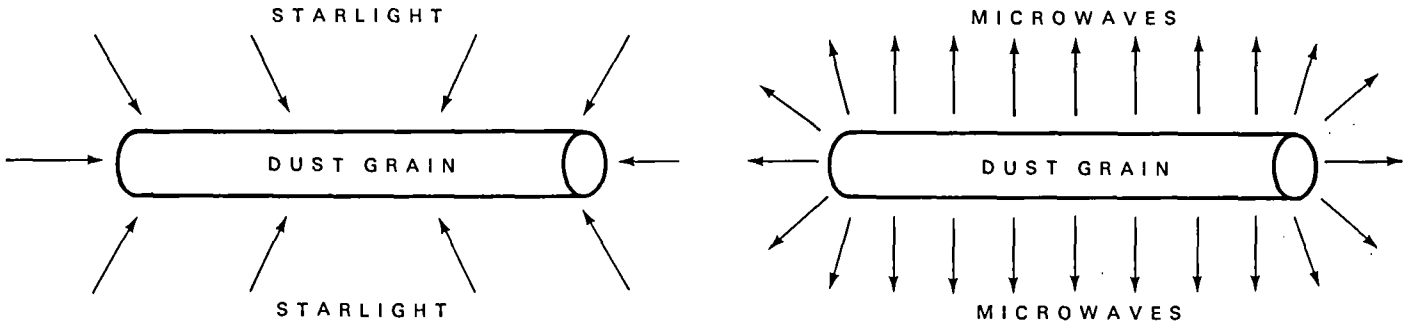
In 1948 Hermann Bondi, Thomas Gold and Fred Hoyle proposed a new model of this kind. Known as the "Steady State" model, it described a universe which is ever-expanding, without a beginning and without an end. As its name implies, the density of matter in this model is held at a *steady* value. How can a system expand and yet retain the same density? This result is achieved in the Steady State model by the injection of new matter continuous-



Earlier epoch

Later epoch

In the expanding steady state universe galaxies like A, B, C, D, move apart when observed from an earlier to a later epoch. New galaxies (filled circles) are created to fill the space generated by expansion so that the universe as a whole does not change from the earlier to the later epoch.



Diagrams © Jayant Narlikar, Bombay

Narrow grains of graphite, about a millimetre long, can form in the intergalactic space. These grains can absorb starlight and radiate it again as microwaves. The microwave background could very well be such a recycled form of radiation.

ly. It is possible to give a mathematical formulation of the creation process *without* violating the law of conservation of matter and energy.

Despite its many attractive features the Steady State model came under a cloud in 1965 with the discovery of a radiation background in microwaves, by Arno Penzias and Robert Wilson. The challenge to the model posed by this observation does not appear so formidable today as it did in the late 1960s, however. In fact, as I propose to show below, the interpretation of this radiation as the relic of the Big Bang has come up with some unexpected difficulties.

The Penzias-Wilson discovery of microwave radiation was hailed as the strongest proof that the Universe has come out of a *hot* Big Bang. The reasons for this belief were: (i) the observed radiation is extremely smoothly distributed and hence does not show any patchiness which would be expected had it come from a large number of isolated sources; (ii) the radiation appeared to have a spectrum very similar to that of the idealized black body. [A black body is an enclosure containing objects which emit and absorb radiation continually, with no radiation escaping from the enclosure or entering it from outside. Theory tells us that such a system settles down to a definite pattern with prescribed intensity of radiation at prescribed wavelengths.]

Both these features were expected from the Big Bang models of the universe. The radiation therefore came to be recognized as the relic of the early hot era in the history of the Universe. There are, however, some difficulties with this interpretation.

One difficulty is that the observed spectrum is not *exactly* that expected from a black body. There are small departures from the black body spectrum which cannot be ignored. This result was pointed out by D.P. Woody and P.L. Richards in 1980, and has remained an awkward point for the Big Bang model ever since.

The second difficulty lies in the extraordinary smoothness of the background itself, and it shows up in two ways. The first problem is concerned with smoothness on a small scale. If, as is advocated, the radiation is the relic of an early hot phase, then it should show some imprint of the changes that the Universe went through *after* that phase. As we mentioned right in the beginning, an important change that took place in the composition of the universe was the formation of galaxies. Thus the matter distribution developed clumpiness and some of it should have been reflected in the background radiation. That no such clumpiness is seen after repeated searches is a worrying matter for Big Bang cosmologists.

The second way in which smoothness poses a problem is known as the *horizon effect*. When we survey the universe out to large distances we see it as it was in the past: because light, by which we see distant objects, travels with a finite velocity. Thus if the universe is ten thousand million years old, we can see objects out to distances of ten thousand million light years (1 light year is the distance travelled by light in one year). However, the radiation background formed when the universe was hardly 300,000 years old. At that time regions separated by more than 300,000 light years would not have been in contact with one another since their fastest means of communication, (the light ray) would not have been able to bridge the gap between them. The present large scale smoothness of the radiation background on the other hand implies that such remotely separated regions were very similar in structure and behaviour. Without physical contact how was this similarity achieved?

While the Big Bang cosmologists engage in theoretical speculations about the early history of the Universe to figure out these mysterious properties of the microwave background, I cannot help feeling that the solution may lie in an entirely different direction and that the microwave background may not, after all, be of relic nature.

The Universe is indeed full of radiation backgrounds at all wavelengths, ranging from radio waves right up to X-rays and gamma rays. With the exception of the microwave background, all are known to be of relatively recent origin, with no possible connexion with the hot post-Big Bang era. Why single out the microwaves?

Fred Hoyle, Chandra Wickramasinghe, V.C. Reddish, and others (including this author) had argued in the late 1960s and the early 1970s that the microwave radiation could be a recycled form of other radiation mainly coming from stars. Dust grains in the intergalactic space, if present in very modest proportions, would be able to do the recycling. N.C. Rana has recently worked out the details of how such a process would operate. Indeed, if a plausible explanation of the microwave background can be found along these lines, the case for a Big Bang cosmology is considerably weakened and the Steady State theory can be revived.

This is *one* of the possible unconventional alternatives to the Big Bang scenario, and I mention it here to emphasize the fact that the cosmological problem is far from being settled yet. Just as better telescopes early in this century expanded man's view and conception of the Universe in an unexpected direction, so I hope, the observing techniques of future years will further widen the cosmologist's vista dramatically.

■ **Jayant V. Narlikar**

Red shift and the Doppler effect

Like Monsieur Jourdain, the hero of Molière's *Le Bourgeois Gentilhomme,* to whom it came as a considerable shock to learn that he had been speaking prose all his life, anyone who has stood on a railway station platform as an express train thunders past with whistle blowing, may be surprised to learn that he or she is quite familiar with the "Doppler effect", one of the keys to modern cosmology.

When a train driver blows his whistle as he approaches a station, he hears a steady sound at a fixed pitch. To the man standing on the platform, however, the sound of the whistle rises in pitch as the train approaches and drops again as the train speeds away into the distance. This is because sound is a succession of waves in the air. As a source of sound approaches, the waves are compressed and the pitch rises, as it recedes, the waves are stretched out and the pitch falls.

The Doppler effect is named after the 19th-century Austrian physicist Christian Doppler who pointed out that the effect applies also to light waves. When light from a moving source reaches the eye, there is a shift in frequency—that is, colour—when the source is moving fast enough. If the source is moving towards us, the light waves are compressed and the light perceived shifts towards the high-frequency, blue end of the spectrum (blue shift); if the source is moving away, the light waves are stretched and the light shifts towards the low-frequency, red end of the spectrum (red shift).

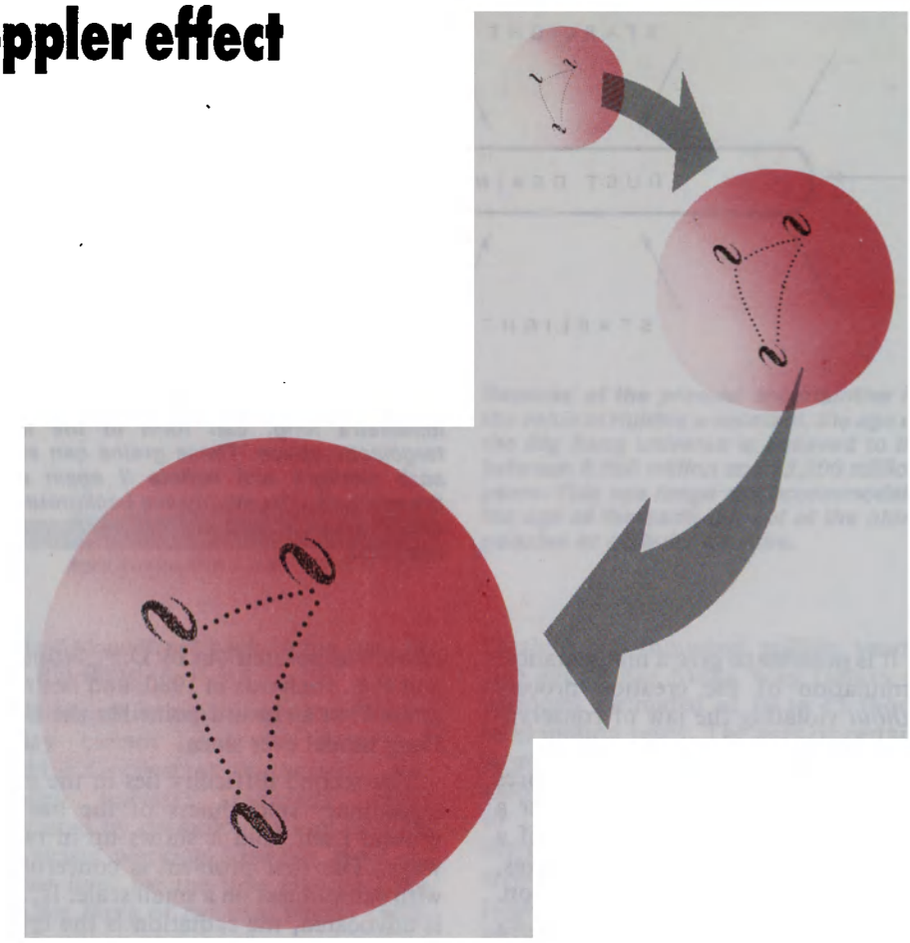


Diagram *Unesco Courier*

The recession of the galaxies can be compared to the way markings on a balloon recede from each other as the balloon is inflated. Illustration shows successive doublings of the size of a "balloon Universe". The points (galaxies) on the balloon recede from each other at a speed proportional to their distance apart.

The importance of red shift became evident early this century with the application of spectroscopy to astronomy. Astronomers began studying the spectra of nebulae. Some, such as the spiral nebula Andromeda, showed blue shifts in their spectra, indicating that, in accordance with the Doppler effect, they must be moving towards us. Others showed red shifts and were therefore receding from us.

Hubble's Law

The application of spectroscopy to astronomy coincided with the building of a succession of giant telescopes at Mount Wilson, in California and the arrival on the scene of the American astronomer Edwin Hubble (1889 to 1953). Working at the Mount Wilson Observatory, he showed that many nebulae were, in fact, galaxies in their own right, developed a classification for galaxies that is still used today (see diagram opposite page), and set about measuring the distance to several of the nearest galaxies.

Hubble soon noticed that galaxies are distributed more or less evenly across the sky and that all galaxies except our nearest neighbours show a red shift in their spectra. In 1929 he announced that his findings showed that the velocity of recession indicated by the red shift is proportional to the distance of a galaxy from us. This became known as Hubble's Law—the direct proof that the universe is expanding.

Since 1929, improved measurement of distances to nearby galaxies has given a more accurate value to the speed of recession as related to distance—the Hubble Constant, as it is known. It is estimated as between 50 and 100 kilometres per second per megaparsec (3¼ million light-years). In other words, for every 75 kilometres of measured recession velocity, a galaxy is about three and a quarter million light years away from us. Hubble's Constant tells us how quickly the universe is expanding, and this in turn enables us to calculate how long ago the Big Bang occurred. The age of the universe, on this basis, is between 15,000 million and 20,000 million years.

Photo © Keystone, Paris

Edwin Hubble (1889-1953).

Galaxies and Quasars

by Nigel Henbest

Photo © Obervatoire de Haute-Provence du CNRS

The Whirlpool Galaxy (M51).

ACCORDING to Greek legend, the pearly band of the Milky Way stretching across the sky is milk spilt from the breast of the goddess Juno. Since Galileo first investigated the Milky Way by telescope, we have known it is in fact composed of stars. It is our own "star island", and the Sun is just one of the 100,000 million stars making the Milky Way Galaxy—often known simply as the Galaxy.

Beyond the Galaxy, thousands of millions of other galaxies stretch out to the limits of the observable Universe. Decades of detailed study have shown that there is a fundamental simplicity to galaxies. They fall into three main types: spirals, irregulars, and ellipticals. The recent techniques of radio, X-ray and infra-red astronomy have shown that some galaxies are much more violent than typical specimens like the Milky Way Galaxy; but it is worth remembering that although the violent galaxies may grab the headlines, they are very much in the minority.

Our Galaxy is typical of a spiral galaxy. These are named for the beautiful two-armed spiral shape visible on photographs—but it is an appearance that is misleading. The bright spiral arms are just one region of the whole galaxy. For a start, there is good evidence that most of a galaxy's matter is not in the form of the stars, gas and dust that we can detect, but consists of some invisible material filling a large volume of space within and surrounding the galaxy. This dark matter makes its presence felt only by its gravitational influence.

The oldest stars of a spiral galaxy fill a large spherical volume of space around the galaxy, and become increasingly concentrated towards its centre. The outer regions of this halo of stars are difficult to detect, but the inner parts show as an orange bulge at the centre of the spiral.

The spiral arms are the most prominent regions of a thin disc of stars, which stretches away from the central bulge like the broad rim of a hat. As well as stars, the galaxy's disc contains gas spread tenuously between the stars, mixed up with small solid particles of interstellar dust. The gas and dust amount to about ten per cent of the mass of stars in the disc, and much of it is clumped into dense molecular clouds where stars are currently being born.

In many galaxies, the spiral shape is a gravitational pattern. As a com- ▶

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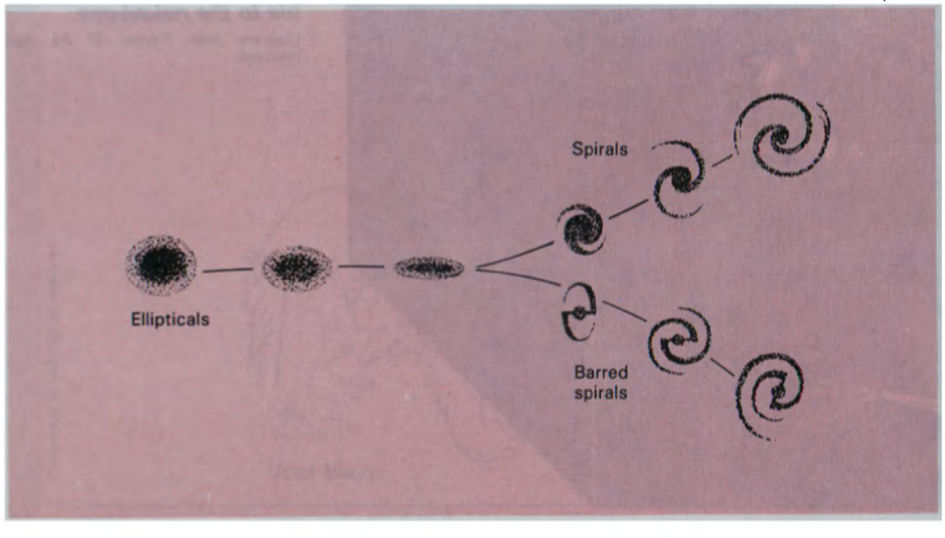

Diagram © Unesco Courier

The American astronomer Edwin Hubble proposed the system of classifying galaxies that is now generally in use. He divided galaxies into ellipticals, spirals, barred spirals and irregulars. Elliptical galaxies are oval shaped and can be up to three times the size of our own galaxy. Spirals, such as our own galaxy, have arms which swing out in a semi-circle from a nucleus. Barred spirals have a bar-shaped nucleus with two arms curving out from the end of the bar. Irregular galaxies, which are not shown in the diagram, are usually somewhat smaller groupings of stars with no particular shape.

▶panion galaxy passes by, it stirs up a ripple in the disc of stars, and this propagates around the disc in a spiral-shaped "density-wave".

Where the spiral is less well marked, it may be due to a chain of exploding stars compressing nearby interstellar gas. Either way, the spiral marks a region where matter is more concentrated and where a lot of bright, energetic stars are now being born.

The Milky Way's companion, the Andromeda Galaxy, is one of the most massive spirals known, weighing as much as 400,000 million Suns (excluding the dark matter). The range of spiral galaxies goes down to about 1,000 million solar masses. Less massive galaxies are not able to maintain a regular disc and stable spiral arms. They have roughly the same proportions of stars, gas and dust, but their unkempt appearance has led to the classification "irregular galaxies". The smallest irregular galaxies are hardly larger than the clumps of stars and gas found strung along the arms of a spiral galaxy.

The third major category of galaxy is the ellipticals. These are simply balls of stars, spherical or elliptical in shape. Although they may be surrounded by dark matter, they contain only a negligible amount of gas and dust. As a result, there are no regions where stars are forming, and no young stars. The elliptical galaxy's stars all date from the time when the galaxy first formed. Ellipticals range from the biggest and most massive galaxies of all, with a million million stars, to the faintest star assemblages which contain less than a million stars.

Galaxies are rather gregarious creatures. Most live in groups, where they are gravitationally bound to neighbour galaxies, and will stay together as the expansion of the Universe carries other groups of galaxies away from them.

The Milky Way lies in a group of about twenty galaxies, called the Local Group. Other members include the Andromeda Galaxy, a giant spiral; the Small Magellanic Cloud, an irregular; the Large Magellanic Cloud, which is on the borders between spiral and irregular galaxies; and many small irregulars and ellipticals.

The Local Group is typical of many groups and larger clusters of galaxies, in containing a diversity of types. But large clusters with a dense concentration of galaxies towards the centre tend to be different. Their galaxies are distributed in a more regular swarm, and X-ray telescopes show that they often contain a pool of very hot gases around the cluster's centre. The galaxies in these clusters are almost entirely ellipticals, or the strange creatures called lenticulars. The latter are lens-shaped galaxies, consisting only of stars, and they are probably spiral galaxies that have been stripped of their interstellar gas and dust as they have ploughed into the cluster's pool of hot gas. The dense packing of galaxies in these rich clusters means that galaxy collisions must be commonplace, and indeed the cluster's centre is often marked by a massive elliptical galaxy which is probably the accumulated remains of galaxies that have collided at the centre of the cluster.

Optical astronomers see a galaxy by the light from its stars. This gives a good measure of the galaxy mass (except for the dark matter) because the matter resides largely in the stars. The starlight can blind astronomers to other kinds of activity in a galaxy, however, and the development of radio, X-ray and infra-red astronomy has led astronomers to galaxies which are producing immense quantities of these radiations. Although these galaxies are in a minority, they are providing new information on galaxies' workings, just as a study of diseases can tell us more about the healthy human body. And they have a fascination of

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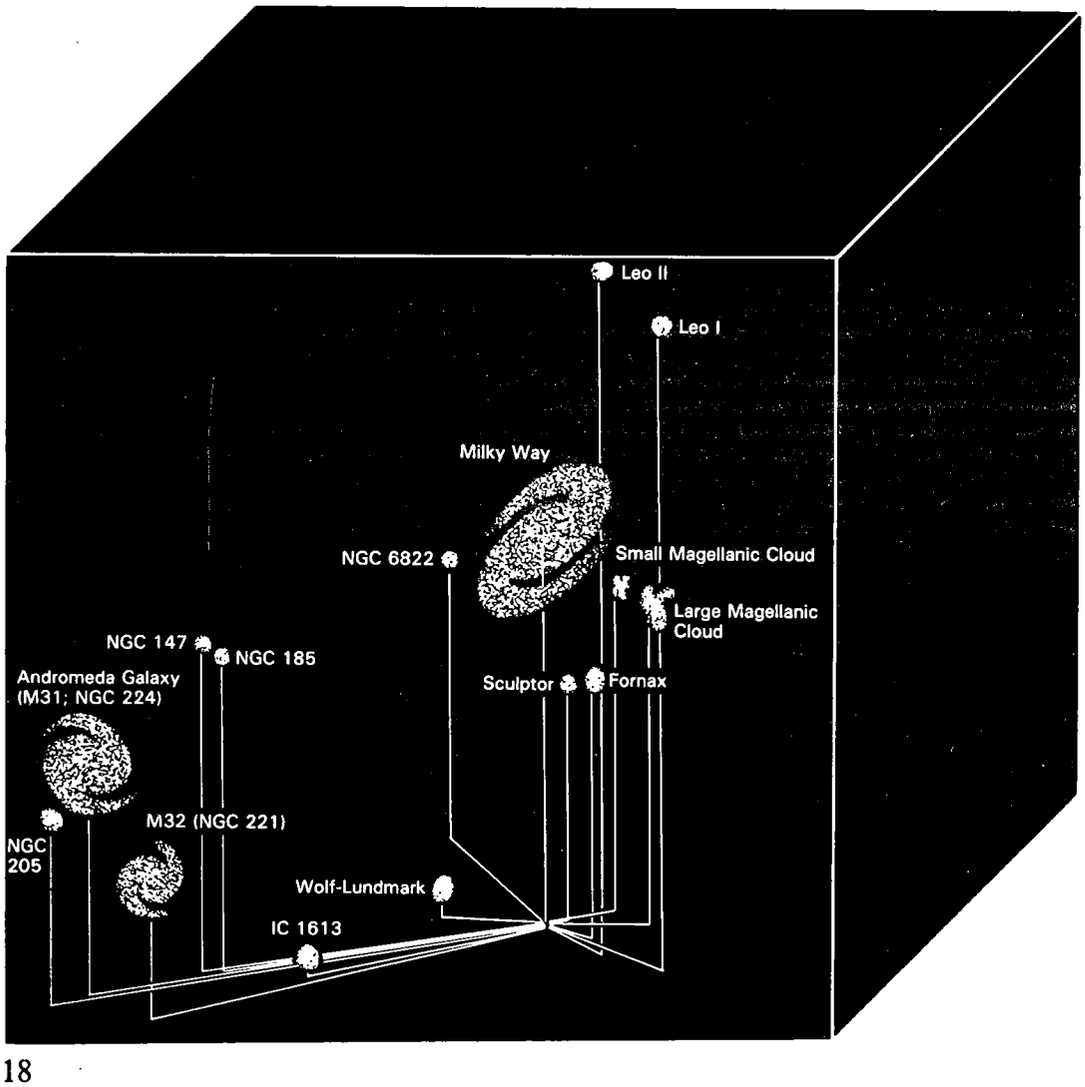
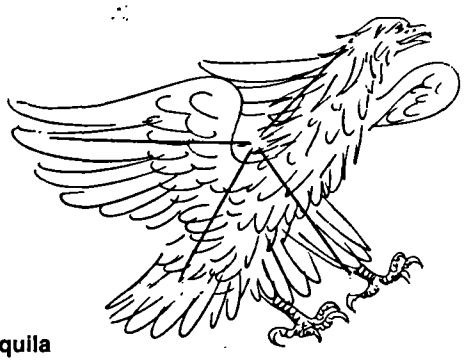
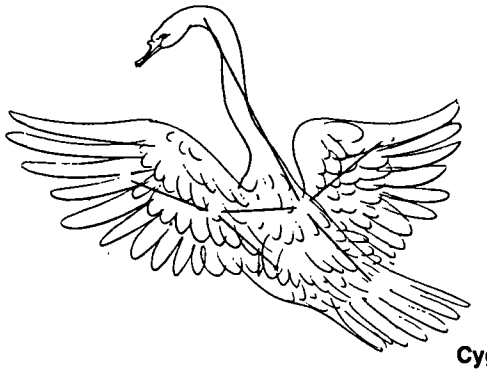


THE LOCAL GROUP, a cluster of some 20 known galaxies including the Milky Way and our own solar system, is represented in this cube each side of which measures some 4 million light-years. Apart from the Milky Way, only the Andromeda Galaxy and the two Magellanic Clouds are visible to the naked eye.

Diagram John Painter © All rights reserved



Aquila



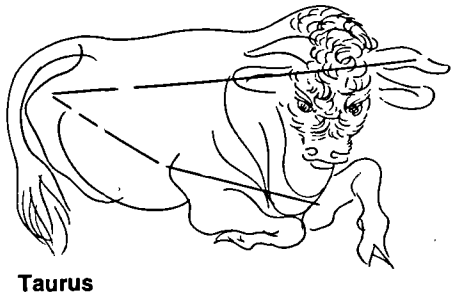
Cygnus

THE STELLAR MENAGERIE

Stars come in a bewildering variety. Some are thousands of times brighter than the Sun, others shining feebly with only a millionth the Sun's output of light. The largest stars, the red giants, are several hundred times larger than the Sun. At the other end of the scale, the smaller stars fall into families that are increasingly bizarre. White dwarfs are only one-hundredth the size of the Sun, neutron stars are smaller still, and black holes are so condensed that the star itself is invisible, and only its gravitational field betrays its presence.

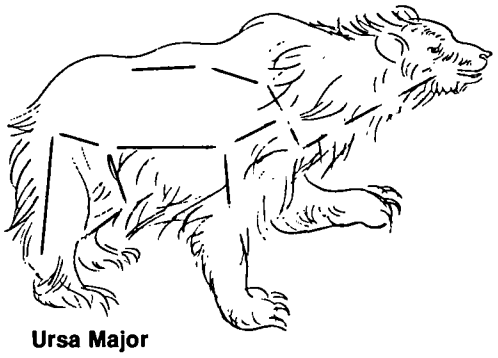
Underlying this diversity, however, there is a very simple pattern. It is a matter only of a star's mass and of its age. Heavier stars produce more energy, and so are generally brighter and hotter than less-massive stars. The differences in size are due to ageing. The Sun, for example, will swell into a red giant, and then collapse to become a white dwarf. As we look around the sky we observe stars of all ages, and hence representing the whole gamut of possible stellar types.

by Nigel Henbest



Taurus

Ursa Minor



Ursa Major

Leo

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THE LIFE AND

Starbirth

Stars are born out of interstellar gas, the tenuous mixture of hydrogen, helium and smaller amounts of other elements that lies between the existing stars of a galaxy. In its natural state, this gas is too rarefied to form into the dense gas globes of stars. But the interstellar medium is disturbed by various kinds of shock waves that compress the gas into denser clouds, and it is here that starbirth occurs.

Astronomers believe that two main kinds of shocks are responsible. The spiral pattern of a galaxy like our Milky Way is a gravitational pattern that rotates at different speed from the galaxy's gas, so it is constantly piling up gas in new locations as the spiral pattern rotates. In addition, the fast-moving gases from an exploding star, a supernova, can sweep up the tenuous gas and compress it into dense clouds. Because of the clouds' large complement of molecules, such as carbon monoxide and alcohol, astronomers call them "molecular clouds".

In the centre of a molecular cloud, the gas is so dense that its own gravity pulls it inwards. This gas is turbulent, so it does not all shrink towards the same central point, but breaks up into dozens of individual fragments of the cloud. Each fragment then shrinks independently, and eventually becomes a star.

These events are hidden from optical astronomers, because the clouds are thick with particles of interstellar dust that block off light. But now radio telescopes can pick up radiation from molecules in the cloud, and infra-red instruments, like the Infra-red Astronomical Satellite, IRAS, can detect heat from the protostars. They have shown that each condensing fragment becomes flattened as a result of its own rotation, and blows off gases at high speeds from either side of this flat disc. These gas flows may trigger the birth of more stars in the vicinity.

The newly-born cluster of several dozen stars is generating radiation and gas flows that eventually disperse the molecular cloud around them. This takes one or two million years—a short time in the astronomer's reckoning. Sometimes the stars are so close that they remain gravitationally bound together as a star cluster, but more often they drift apart. About one-third of all stars end up single, like the Sun; the other two-thirds take along a close companion from the original cluster and end up as double stars. ■

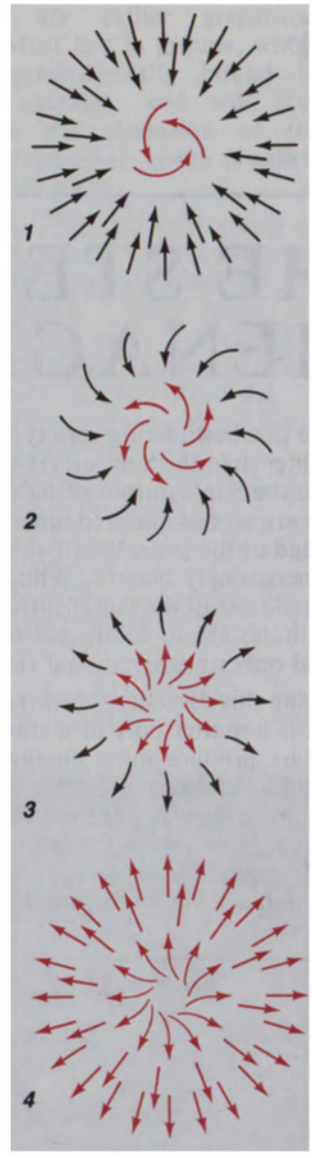

Diagram © Unesco Courier

(1) A star's life begins when it condenses out of dust and gas scattered in space. (2) As gravity begins to act, the embryo star starts to shrink. (3) As it shrinks, the temperature near the middle rises until it becomes high enough for fusion to take place. (4) The body has now become a real star, radiating huge amounts of energy.

Main sequence

The compression within a protostar heats up its interior to some 10 million degrees, and at this point nuclear reactions begin to convert its hydrogen gas into helium. The reaction releases energy, which seeps up through the star and shines out from the surface. The energy source also opposes the in-pull of gravity, so the gas globe stops shrinking and remains constant.

The balance between energy production and gravity is so stable that the star remains very much the same for millions of years, or more. This period of "hydrogen-burning" is in fact the longest phase of a star's life. Traditionally, astronomers call stars in this phase "main sequence stars", because their properties follow a well-defined pattern. All main sequence stars of the same mass have a very similar luminosity and surface temperature (the latter dictating their apparent colours). The more massive a main sequence star, the brighter and hotter it is; the less massive it is, the dimmer and cooler. The Sun and Sirius are both typical main sequence stars, for example, but because Sirius is twice as heavy as the Sun, it is 20 times brighter and has a surface temperature of 10,000°Centigrade as compared to the Sun's 5,500°Centigrade surface.

Eventually a main sequence star will consume all the hydrogen in its central region where temperatures are high enough for nuclear reactions to occur. A star like the Sun reaches this point after some 10,000 million years—fortunately for us, a long way in the future, as the Sun is currently 5,000 million years old. The highly-luminous massive stars are ripping through their central fuel supplies much more quickly, and reach the end of their main sequence phase after only a few million years. ■

Red giants

Once a star's core is bereft of hydrogen, and is composed of helium created by the reactions, it contracts under its own gravity. Hydrogen immediately around the core then begins to "burn" to helium, in a thin shell. To compensate for the collapse of its core, the outer layers swell out, to about a hundred times its previous size. The radiation from its interior now has to spread out over more surface gases, and so cannot heat it as much. The temperature falls to only about

DEATH OF A STAR

White dwarfs

3,000°Centigrade, and the colour of the star changes from the white or yellow of a star like Sirius or the Sun to a dull red. The swollen, reddish star is now a red giant.

The outer gases of a red giant are held so tenuously that they wobble in and out, causing the star's brightness to go up and down over a period of about a year. The more massive stars expand to become even larger, and are termed supergiants. In some, the outer layers oscillate in and out with a very precise period, whose length is related to the star's mass and hence to its brightness. These Cepheid variable stars are immensely useful to astronomers measuring distances in the Universe. ■

After its red giant phase the final fate of a star depends on its mass. If it is similar to the Sun, the star sheds the tenuous outer layers of its red giant body. This gas spreads into space as a glowing ring, known to astronomers as a planetary nebula. (The name has nothing directly to do with planets, incidentally; the rings simply look rather like Uranus or Neptune when seen through a small telescope.)

The star's core is left as a very compact little object, a white dwarf star. It contains almost as much mass as the Sun, but packed into a sphere only the size of the Earth. The white dwarf is made up of matter in an unusual state. Like other stars, it consists of atomic nuclei and electrons—the components of atoms broken apart in the heat of a star's interior. While other stars are gaseous, with pressure provided by the fast speed of these constituents, a white dwarf is effectively solid, because its matter is so compressed that the electrons are packed together as tightly as they will go. This is an example of what physicists call "degenerate matter".

A white dwarf has no source of energy, no interior nuclear reactions. It begins life extremely hot, with the residual heat from its days as a star's core. But as time goes by, it radiates its heat away to space, and eventually ends up cold, dark and forgotten as a "black dwarf". ■

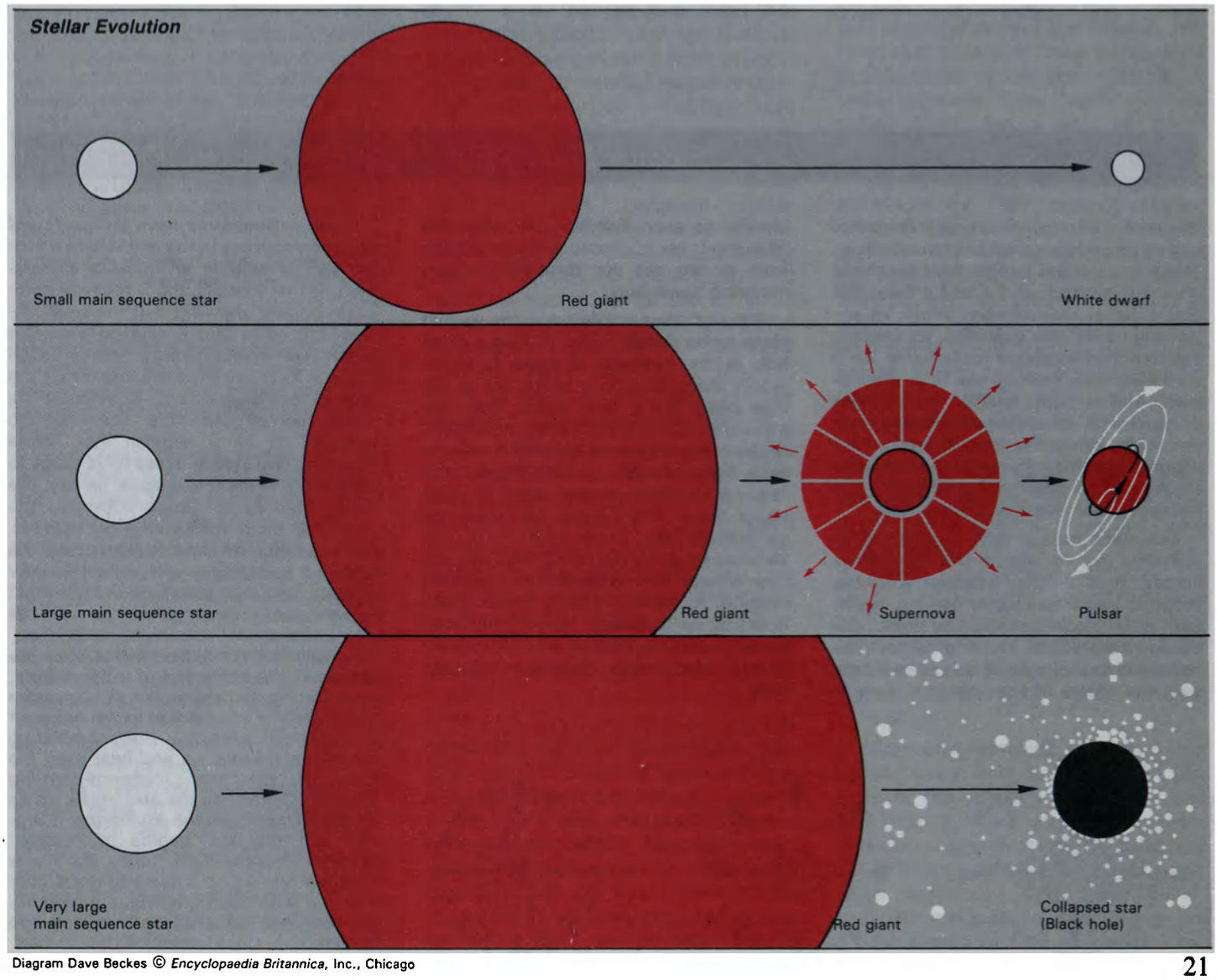

Diagram Dave Beckes © *Encyclopaedia Britannica*, Inc., Chicago

Supernovae, neutron stars, pulsars

A heavy star goes out with a bang. At the end of its phase as a red giant (or a Cepheid variable), the nuclear reactions near its centre become unstable, and the star blows itself apart, as a supernova. In this colossal explosion, the supernova briefly shines as brightly as a thousand million Suns.

As the outer layers of gas blow themselves off, the core is powerfully squeezed, and it collapses until it is only about 20 kilometres across—only the size of a large city. During the collapse, its electrons combine with protons to make neutrons, and the collapse halts when the neutrons are packed together—another example of degenerate matter, but this time involving neutrons rather than the electrons found in white dwarfs. A typical neutron star weighs a little more than the Sun, and its small size means that its density is incredible: a pinhead of neutron star matter would weigh a million tonnes.

As neutron stars rotate, they give out radiation that appears to "flash". Radio astronomers at Cambridge first picked up these pulses of radiation in 1967, and called their sources "pulsars". Pulsars, or neutron stars, often give out flashes of X-rays and gamma rays, too, and in a few cases, flashes of light. These pulses show that the small stars rotate unbelievably quickly. The pulsar in the Crab Nebula, the remains of a supernova that exploded 900 years ago, turns 30 times per second; while a pulsar discovered in 1982 rotates an incredible 642 times every second! ■

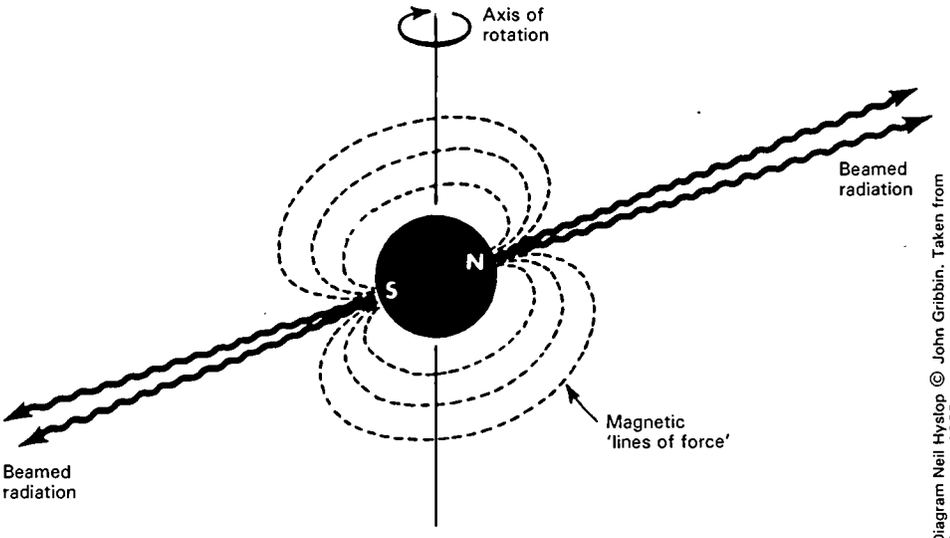

Diagram Neil Hyslop © John Gribbin. Taken from *Spacewarps*, 1983

LIGHTHOUSES IN THE SKY. As neutron stars rotate, they emit beams of radiation which we perceive as flashes as the beams flick past us at regular intervals, just as a sailor sees the flashing beam of a distant lighthouse.

Black holes

The centre of a very massive star cannot end up as a white dwarf or a neutron star. There is a natural weight limit for these shrunken entities, of 1.4 and 3 times the Sun's mass, respectively. When an extremely heavy star explodes, its collapsing core may be above these limits. As it shrinks in size, nothing can stop the collapse; and as it gets smaller, the strength of gravity at its surface increases continuously. When the core is only a few kilometres across, its gravity becomes so strong that nothing—not even light—can escape. It has become a black hole.

The black hole is thus a region of irresistible gravity just a few kilometres across. It is a hole, because anything dropped into it can never get out again; and it is black because no light can escape from within. The original core has collapsed to a very small size somewhere near the centre of the hole, but there is literally no way of finding out what has happened to it, because no radiation from it can get out through the surrounding black hole.

Although theory tells astronomers that black holes should exist, finding a black hole in the darkness of space is rather worse than locating a black cat in the coal cellar on a dark night! The only giveaway is its gravity. Since two-thirds of the stars are paired up with a companion, there should be many black holes teamed up with normal stars in orbit about them. The normal star could be sufficiently far away that it is not swallowed up by the black hole, but still near enough for the black hole to pull off some of its surface gases. These gases flow down towards the black hole, heating up in the processes and emitting X-rays before they disappear into the hole.

X-ray astronomers have indeed found radiation sources in the sky where a visible star is orbiting an invisible companion. In many cases, the X-rays are coming in pulses, showing that the small unseen star is in fact a neutron star. But when they investigated a source called Cygnus X-1, astronomers found that the unseen companion star is at least six times heavier than the Sun—far too massive to be a neutron star. More recently, two similar cases have come to light in our nearest neighbour galaxy, the Large Magellanic Cloud. Although the evidence must necessarily be indirect, the existence of black holes among the stars of our Galaxy and others is now proven to the satisfaction of most astronomers. ■

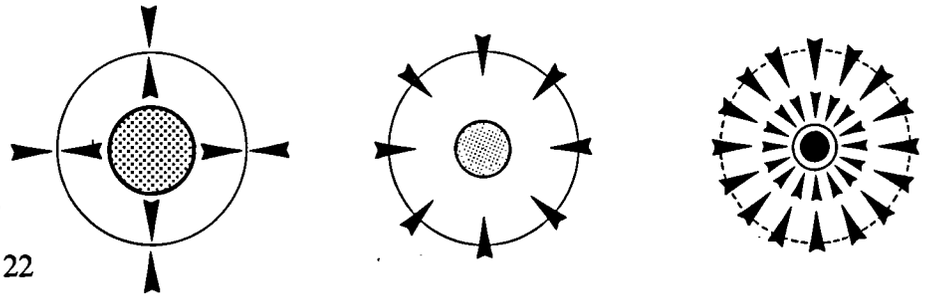

Diagram *Unesco Courier*

Diagram, illustrates, from left to right, the stages in the formation of a Black Hole. Left, during the stable life of a massive star a state of equilibrium exists between gravitational pressure (inward-pointing arrows) and radiation and heat from the core of the star (outward-pointing arrows). Centre, as the star burns up its supply of hydrogen the equilibrium is broken and the star begins to collapse towards its core. Right, finally, the star is crushed into a tiny volume of great density and with such enormous gravitational pull that not even light can escape from it.

The scale of space

For the relatively short distances within the Solar System, astronomers can use the kilometre as a unit. But even the distance from the Earth to the Sun, 150 million km, is becoming a little too large to work with. Solar system astronomers often take this distance as their unit and call it "one astronomical unit". In this way, the distance to Pluto, the outermost planet, becomes a convenient 39 astronomical units.

Another measure of an astronomical distance is given by the time taken for light to traverse it. The Earth-Sun distance is 8 1/3 light-minutes; the diameter of Pluto's orbit is 11 light-hours. The latter dimension, while minuscule on the scale of the Galaxy, is similar to the size of the compact powerhouse within a quasar.

The nearest star, Proxima Centauri, lies 7,000 times further off than Pluto, at 4.2 light-years. The brightest stars in the sky lie at a variety of distances, Sirius at 8.6 light-years, for example, and Arcturus at 36; Deneb (in Cygnus) is among the most distant of the "first magnitude" stars, at 1,500 light-years away. But this is just on our doorstep in the whole Galaxy: it is 30,000 light-years from the Sun to the Galaxy's centre; and the Milky Way is some 100,000 light-years in diameter.

Irregular galaxies are considerably smaller than the Milky Way, and most spirals are slightly smaller. Our neighbour, the Andromeda Galaxy, is one of the largest spirals known, with a diameter of 150,000 light-years. The largest ellipticals are bigger still, with diameters of up to a million light-years. These sizes refer to the extent of a galaxy's stars. The beams ejected from a radio galaxy can stretch much further out, to make these objects the largest connected structures in the Universe.

The nearest galaxy to the Milky Way is the Large Magellanic Cloud, at 170,000 light-years. Our Local Group of galaxies is five million light-years across. The nearest large cluster of galaxies, the Virgo cluster, is about 50 million light-years away. Typical large clusters of galaxies are about 30 million light-years across. They are often grouped into superclusters. These assemblies of clusters are typically 200 million light-years in extent, and they often form the denser parts of filamentary structures that stretch over 500 million light-years or more. The clusters of galaxies are gravitationally bound and will remain roughly the same size; the superclusters and filaments will grow with the expansion of the Universe. ■

Photo © Mount Wilson and Palomar Observatories, Pasadena, California

The great spiral galaxy in the Andromeda constellation.

CONTINUED FROM PAGE 18

their own, for some active galaxies, the quasars, are the most powerful objects in the Universe.

Astronomers now recognize two different kinds of active galaxy. The "starburst galaxies" are spiral or irregular galaxies where a large proportion of their interstellar matter is turning into stars all at once. The light from these new stars is hidden by dense dust clouds around them, but their energy eventually escapes from the clouds as infra-red, "heat" radiation. Astronomers only vaguely suspected the existence of starburst galaxies before 1983, when the first orbiting infra-red telescope was flown on the Infra-red Astronomical Satellite (IRAS). IRAS discovered thousands of starburst galaxies, some emitting a hundred times as much heat as light, and the analysis of the results is still under way.

The strongest active galaxies however fall into the second class, those with a central "powerhouse". This is a small region of concentrated power in a galaxy's centre, probably no larger than the Solar System, and producing an amount of energy equivalent to the output of up to a million million Suns. The powerhouse can also send energy out into space, in narrow beams.

The largest of the elliptical galaxies frequently have a powerhouse that gives out little radiation itself (and so is not easily detected by optical, radio or X-ray telescopes), but puts its power into two oppositely directed beams. These probably consist of high-speed electrons, like the beam from a television tube's electron gun. The beams speed out into space on either side of the galaxy, still giving little hint of the energy in flow. But eventually they strike the very tenuous gas that surrounds the galaxy, and they surrender the energy. It goes into a random mixture of magnetic field and chaotic electrons that generates radio waves, by a process called synchroton radiation. A radio telescope thus "sees" not the galaxy itself, but a pair of bright clouds, one on either side of the galaxy.

The powerhouses in spiral galaxies are not so coy. They generally produce a lot of light, X-rays and radio waves directly. The most common type, and the best-studied, are Seyfert galaxies. Carl Seyfert, working in America in 1943, first investigated spiral galaxies with a tiny bright point of light at the centre. As well as this inexplicable light source, he found that the central regions of the galaxies contain gases moving at high speed.

The next step came twenty years later, when astronomers found that some radio sources coincided with small points of light in the sky. Although these looked like stars, the red shift of their light showed they were very distant objects, being carried away by the expansion of the Universe. Their conflicting properties led to the name "quasi-stellar objects", later shortened to quasars.

More recent research has shown that quasars are simply more powerful versions of the galaxy cores that Seyfert had studied. With sensitive electronic detectors, astronomers have found that the brilliant powerhouses are in many cases surrounded by a faint "fuzz" that corresponds to the galaxy we would expect to find there—and the ▶

▶fuzz generally shows a spiral shape. Both quasars and the centres of Seyfert galaxies are constantly fluctuating in brightness, so it's quite likely that they are one and the same phenomenon, caught at different levels of activity.

The powerhouse in a quasar is a truly diabolic inferno. Some quasars change their output of X-rays in only a couple of hours, implying that the powerhouse is just a few "light hours" across—only the size of the Solar System. Yet in the largest outburst yet seen from a quasar, this tiny region was emitting the power of over a thousand normal galaxies!

Most astronomers believe there is only one possible source for concentrated power of this magnitude: the powerful gravitational field around a black hole. As gas spirals downwards into a black hole, as much as 40 per cent of its mass can be converted into energy. A spiral galaxy would certainly have enough gas to "feed" the black hole of a quasar lurking in its centre.

There is more of a problem in explaining the powerhouses in elliptical galaxies that eject the electron beams, because these galaxies are relatively gas-free. But even here there is a solution: the gravitational pull of the black hole can rip stars apart as their orbits bring them too close to the hole, and the spilt gas from the disrupted star can then spiral inwards.

Backing up this theory are sensitive measurements of two nearby active galaxies. The elliptical galaxy M87 is a radio galaxy, and a team of British and American astronomers have discovered that the stars near its centre move as if they are constrained by the gravity of a compact, invisible object some 5,000 million times heavier than the Sun. Only a black hole could be this heavy yet so small. And an international team studying the motions of gas in the Seyfert galaxy NGC 4151 have concluded that it is orbiting a black hole about 500 million times the Sun's weight.

An active galaxy's outbursts must depend not only on the presence of a central black hole, but also on gas currently spiralling inwards. About 10 per cent of large spiral galaxies are Seyfert galaxies, and most astronomers believe they are not continuously active. To turn the statistics around, then, it is possible that *all* spiral galaxies contain a central black hole, but that they are fuelled for only ten per cent of the time. In that case, the distinction between a normal galaxy and an active galaxy becomes blurred. Perhaps ordinary galaxies, like the Andromeda Galaxy and even our Milky Way, contain a dormant black hole, have suffered outbursts from a central powerhouse in the past—and may possibly do so again.

■ **Nigel Henbest**

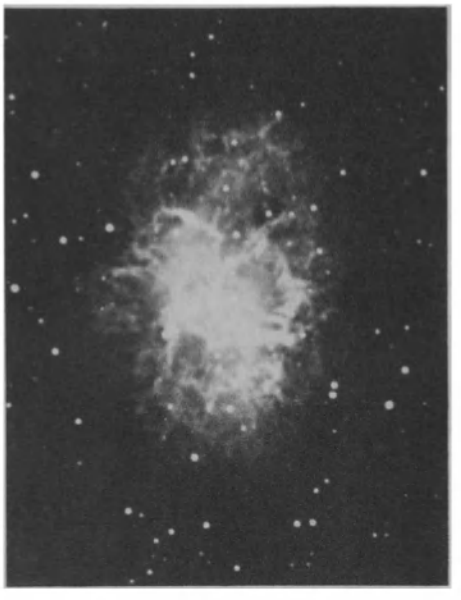

Photo © Observatoire de Haute Provence du CNRS

The Crab Nebula, produced by the explosion of a supernova in 1054.

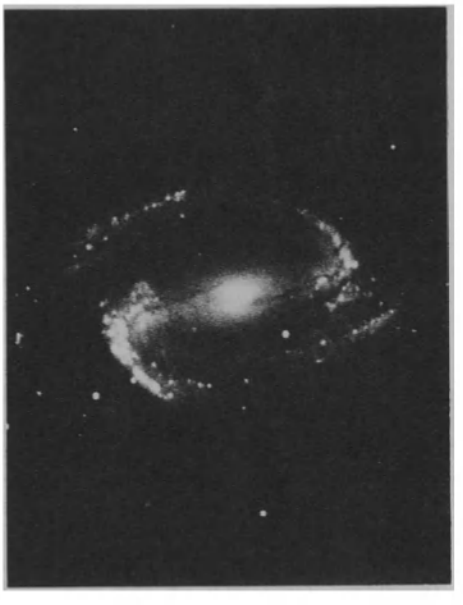

Photo © IPS, Paris

The barred spiral galaxy NGC 1300.

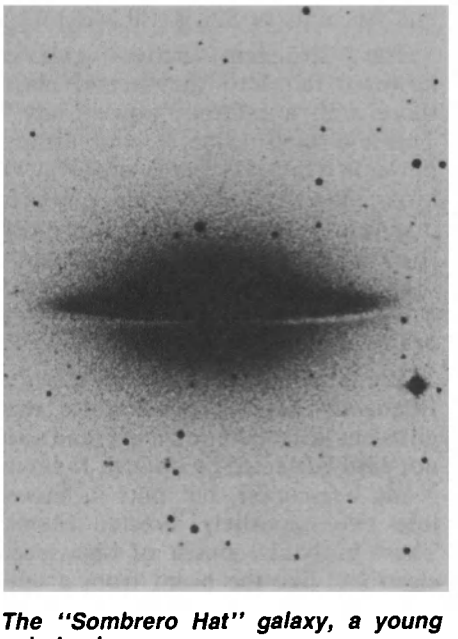

Photo © Royal Observatory, Edinburgh

The "Sombrero Hat" galaxy, a young spiral galaxy.

The

THE most important feature of the physical world around us—the Universe—is its structure. Rather than being scattered haphazardly, the matter that surrounds us is, to a large degree, assembled in various formations or structures. Structures of one type constitute the building blocks from which are formed structures of a second level that are considerably larger in spatial dimension. These second-level structures are in turn assembled into third-level structures and so on, but, as we shall see later, not *ad infinitum*. In other words, there is a hierarchy of structural levels.

If we confine ourselves to astronomical scales, any enumeration of these structures must necessarily start with the Earth and the other planets of the solar system whose centre is the star we call the Sun. Hundreds or thousands of millions of stars are grouped in galaxies like our Galaxy, the Milky Way, or the nebula in Andromeda. This is the second astronomical structural level. Galaxies, however, are unevenly distributed in space and form huge clusters or superclusters. It is these structures that are of interest in cosmology—the study of the Universe itself.

For the non-expert in astronomy the unit of distance of which he can most easily form a mental picture is the light-year—the distance travelled by light in one year. A light-year is approximately equivalent to ten million million (10^{13}) kilometres. For comparison let us

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structure of the Universe

by Yacov Borissovich Zeldovich

recall that it takes light eight minutes to reach the Earth from the Sun, but approximately four years from Proxima Centauri, the nearest star. Proxima is therefore four light-years away.

The diameter of a typical galaxy may be as little as ten thousand or as much as one hundred thousand light-years, and the distance from the Earth to the nearest giant galaxy, Andromeda's nebula, exceeds two million light-years. Galaxies are grouped together in clusters, and the diameters of the big clusters of galaxies are of the order of ten million light-years. Clusters themselves group together in superclusters that are between one hundred million and three hundred million light-years across.

Big clusters of galaxies, containing thousands of galaxies and more, have been known for a long time because they stand out clearly in the sky. Figure (1) overleaf, for instance, shows the great cluster of galaxies in the direction of (but far beyond) the constellation Coma. But superclusters have only been unambiguously identified as a result of progress achieved in observational astronomy in the past decade.

The structure of the superclusters could not be determined as long as the photographs studied in stellar atlases showed only a projection of a galaxy's position on the celestial sphere. If galaxies seem to be alongside each other in photographs, it does not follow that they are actually near one another. It is quite possible that such galaxies are at different distances from the Earth and that it is only by accident that they lie almost along the same line of sight as viewed from the Earth. The true position of galaxies in space can be ascertained only by constructing a three-dimensional picture. To do this a third co-ordinate—the distance to the galaxy—must be added to the two angle co-ordinates which give the position of the galaxy on the celestial sphere (these are analogous to geographical latitude and longitude).

The distances to the distant galaxies are found using Hubble's Law, which tells us that the velocity at which a distant galaxy is receding from us is proportional to its distance from us. The coefficient of proportionality is called Hubble's constant (see page 16). The velocity of a galaxy can be determined from the Doppler effect on the light coming from that galaxy, that is to say by measuring its "red shift" (see page 16).

Red shifts have now been measured for more than ten thousand galaxies. Using the distances to the galaxies thus obtained, three-dimensional pictures of the distribution of the galaxies in space have been constructed with the aid of computers. The results were unexpected.

Why unexpected, and what distribution of galaxies would we have expected *a priori?* If all structural levels of matter are qualitatively similar to each other and differ only in spatial dimensions, then something not unlike the structure depicted in Figure (2), where every dot represents a galaxy, should have been obtained.

In other words, on the basis of our previous knowledge it was quite natural to suppose that galaxies are grouped in clusters in exactly the same way that stars are grouped in galaxies. The existence of such clusters, as in Coma (see Figure 1), would furnish an additional argument in support of such an hypothesis.

The reality, however, proved to be quite different. An overwhelming proportion (80 to 90 per cent) of the galaxies proved to be concentrated in greatly extended, thread-like (filamentary) patterns with a thickness of less than thirty million light-years and a length of up to three hundred million light-years. Adjacent threads intersect each other forming a combined, three-dimensional structure like a network of cells, or a honeycomb. This structure is usually called a supercluster system, a boundary being conventionally drawn between separate superclusters where the threads become finer and more distinct. The large clusters of galaxies, of the type depicted in Figure (1), contain an extremely small proportion (less than ten per cent) of all the galaxies, and as a rule they are situated near the points of intersection of the filamentary structures.

A schematic, very simplified picture of the distribution of the galaxies is given in Figure (3). Superclusters occupy a very small portion (about ten per cent) of the volume of the Universe as a whole. The remaining space contains hardly any galaxies. In a projection of the visible celestial sphere these huge voids disappear completely because the superclusters lying behind these voids are seen through the gaps. The same thing happens with the filamentary structures. Only the big clusters, having a very marked concentration towards the centre, still stand out (as in Figure 1). This is why it was necessary to construct a three-dimensional picture.

The structures as represented in Figures (2) and (3) are clearly visible to the eye and it is impossible to confuse them. But how can they be distinguished from each other mathematically and quantitatively? The problem is rather like one we encounter in everyday life. We instantly recognize someone we know in a photograph or on meeting him, but how can we describe him in words so that others can recognize him? (It is even more difficult to teach a computer to recognize someone from his or her external appearance). ▶

▶ Figures (2) and (3) have been drawn so that the average density of the galaxy dots and the density contrast (defined as that portion of the volume of space in which most of the galaxies are contained) are identical. We can easily tell them apart. At the same time a strict mathematical criterion is essential in order to discern the structures because the human eye is capable of seeing structures where none exists. The story of the "canals" on Mars, seen by observers with poor telescopes only to vanish from view when more powerful instruments were used, is a good example (see opposite page).

Our Moscow team recently succeeded in establishing such a criterion. Leaving aside the mathematical details, this criterion can be explained as follows. Suppose your problem is to cross from one end of Figure (2) or Figure (3) to the other, but the Figure represents the whole of the infinite Universe. You are entitled to touch only upon those places where there are galaxy dots. Moreover, your physical possibilities are limited—you cannot make steps or leaps of more than a certain length. The question is: what is the maximum length of step you must be capable of in order to perform the task of completing a voyage through the whole of the Universe?

The answer depends on the ratio of this maximum length of step to the average distance between the galaxy dots, which we may call the critical parameter.

If we look at Figures (2) and (3), we see that when crossing the structure shown in Figure (2), it is necessary to take big leaps between the clusters (so a maximum length of step of the order of the distance between the clusters is necessary) whereas it is possible to cross the structure in Figure (3) in small steps, and the maximum length of step in this case does not exceed the distance between the galaxies within the filament. Consequently, the critical parameter in the first case turns out to be considerably greater than in the second. For the purposes of comparison we can consider a third case, where the galaxy dots are disposed quite haphazardly and independently of each other. In this case the parameter acquires an intermediate value—close to three.

So which structure does the real Universe resemble? When we investigate a real three-dimensional distribution of galaxies we find that the parameter is significantly less than three and close to that obtained for the filamentary structure in Figure (3). This tells us, in rigorous mathematical terms, that the honeycomb structure of the superclusters that we perceive with our own eyes is real.

Observations also prove that on a scale of the order of a thousand million light-years, which is twice as much as the maximum scale of a supercluster, the distribution of matter in the Universe is, to a high degree of precision, homogeneous (the same everywhere), isotropic (it looks the same in all directions) and unstructured. Deviations from the average density on this scale do not exceed ten to twenty per cent. On still larger scales the degree of homogeneity and isotropicality is even greater. Therefore, non-homogeneous structures of a higher level than superclusters do not exist. Superclusters are the biggest structures in the universe, at the top of the hierarchy. On bigger scales, the Universe is uniform.

How can we explain this observed structure? The general characteristics of the Universe, such as its overall homogeneity, isotropy and its expansion are vividly described by means of the "hot Big Bang" model. To explain the origin of the galaxies, their assembly into clusters and superclusters, we must assume that at the time of the Big Bang there were very slight inhomogeneities (unevennesses or "lumpiness") in the distribution of matter. In recent years some very attractive and exciting theories have been proposed to explain these initial inhomogeneities (see article page 8). But here we shall consider only how those inhomogeneities grew as the Universe got older.

It is easy to investigate the evolution of inhomogeneities (lumps in the universe) as long as they are small. The lumps grow because because gravity pulls more matter onto them and, although they start small, ultimately they become more pronounced. As they grow, the equations needed to describe their behaviour become more complex, but I have succeeded in showing that the first solid structures to appear must have had the form of a flat thin cake with sharp edges. Because of this the theory became known as the "pancake" theory of galaxy formation. In the course of time the pancakes grew until they intersected each other. The density of the matter on the lines of intersection increases further as gravity does its work and it is precisely these lines that form the cellular network structure during further evolution. Numerical calculations made on computers in Moscow and by other teams of experts give a picture of a large-scale honeycomb structure on the whole similar to the one observed, although there is not yet complete agreement on all the details.

Great advances are being made in cosmology as a whole and in the theory of the structure of the Universe. Further work remains to be done but the rate of progress is such that we can expect real advances towards finding the answers to these profound questions within the lifespan of this generation.

■ **Yacov Borissovich Zeldovich**

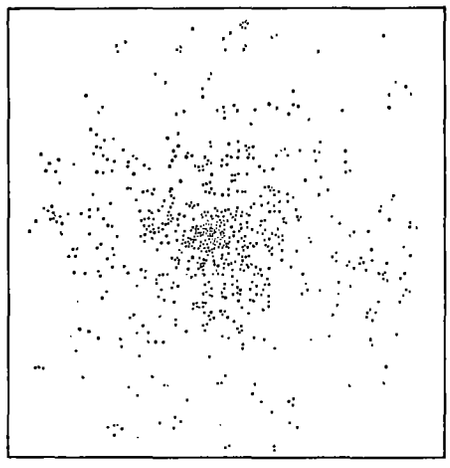


Figure 1

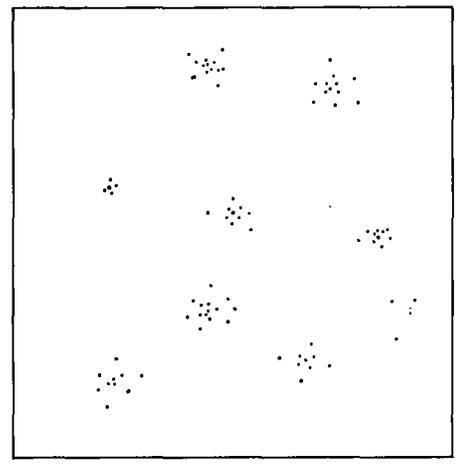


Figure 2

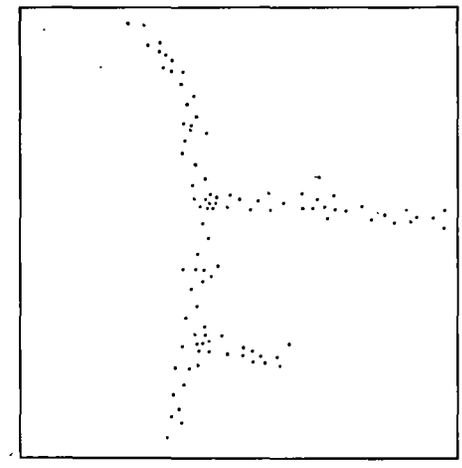
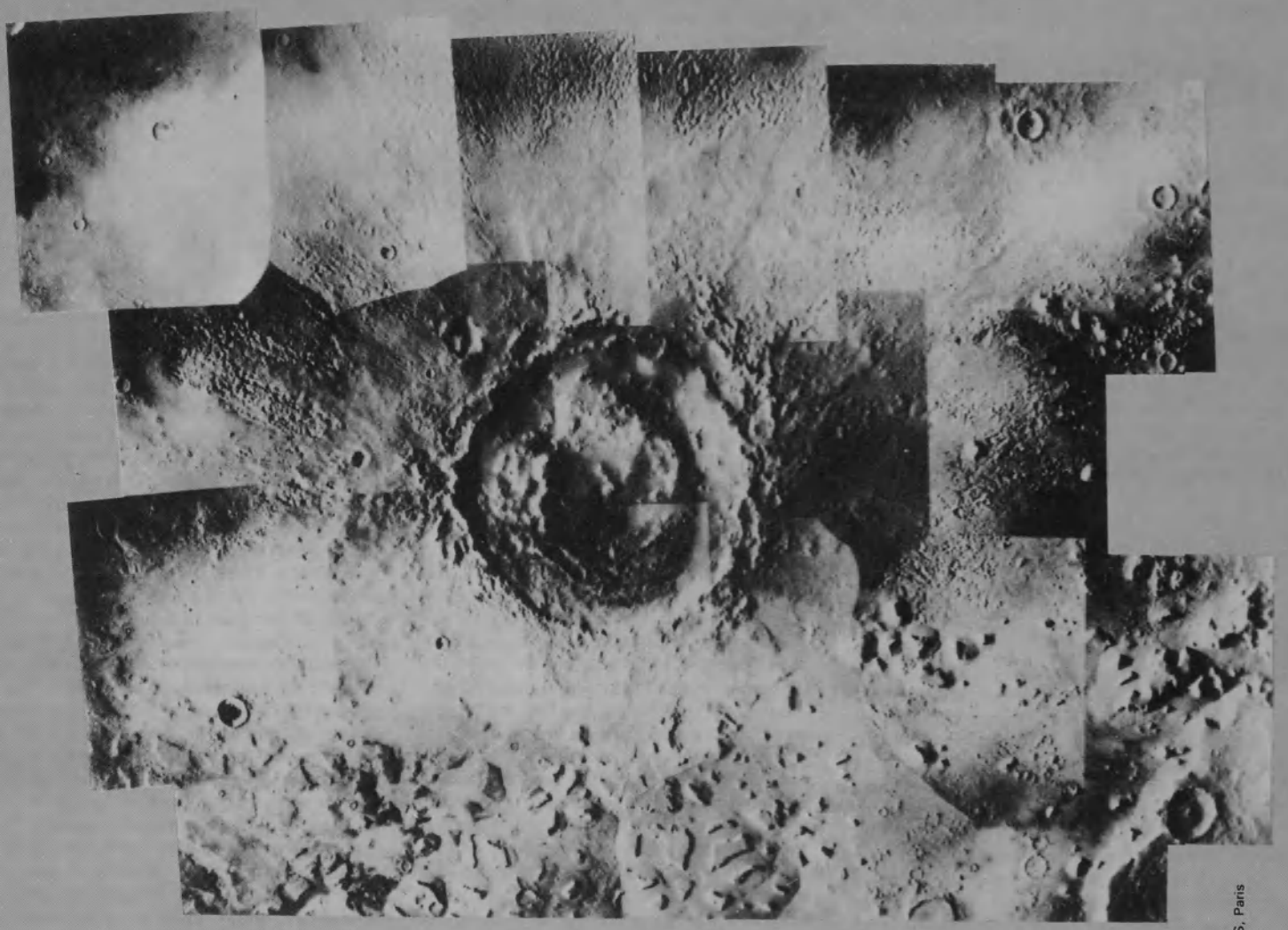
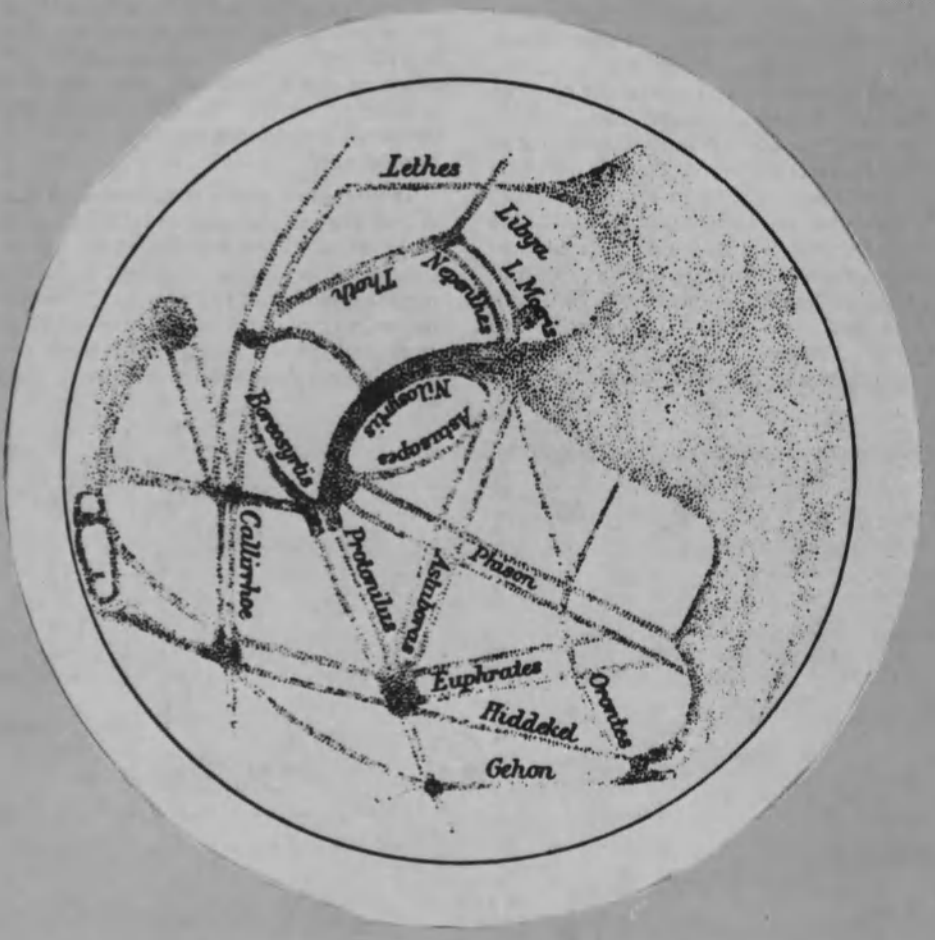


Figure 3



Photos © IPS, Paris

The canals of Mars



The difficulties of making accurate astronomical observations through the earth's turbulent atmosphere are illustrated by the strange controversy about "the canals of Mars". The Italian astronomer Giovanni V. Schiaparelli (1835-1910) observed in 1877 that Mars had strange markings which he called *canali,* a word which was wrongly translated into English as *canals* instead of *channels.* Schiaparelli's ideas were taken further by the American astronomer Percival Lowell (1855-1916) who claimed that the waterways were irrigation canals constructed by intelligent beings. "A mind of no mean order would seem to have presided over the system we see," he wrote, "a mind certainly of considerably more comprehensiveness than that which presides over the various departments of our own public works." These theories inspired a host of science fiction stories and were only laid to rest in the mid-1970s when the US Viking missions revealed Mars's dusty, crater-pitted surface but not a sign of "canals". Right, drawing of Mars and its *canali* made by Schiaparelli in 1888. Above, mosaic of Viking Orbiter-2 photos, taken from 7,600 km, shows a large meteorite impact crater on Mars.

The origin of the elements

AS the Universe began to cool after the Big Bang in which it was born, clouds of gas were able to collapse under the pull of their own gravity and form stars. But those first stars did not contain the rich diversity of chemical elements that we find on Earth today. Only hydrogen and a little helium—about 20 per cent of the total matter—were created in the Big Bang itself; all of the other elements, including the carbon in your body and the oxygen in the air that you breathe, have been manufactured inside stars and spread across space by stellar explosions—supernovae.

A first generation star, containing only hydrogen and some helium, would have formed as a ball of gas, contracting under the pull of gravity and getting hotter in the middle, as gravitational energy was converted into heat. Higher temperatures mean that the particles in the heart of the young star move faster and collide with one another more violently. At a few thousand degrees, electrons are stripped from their atoms, leaving a sea of protons (hydrogen nuclei) constantly colliding with one another. And at a temperature of about 10 million degrees K two protons that collide with one another stick together. Each of these protons carries a positive charge, but when they stick together the pair emit a positively charged counterpart of the electron, called a positron, and one of the protons thereby becomes converted into a neutron. The combination of one proton and one neutron forms the nucleus of an atom of heavy hydrogen, deuterium. And when that deuterium nucleus collides with another proton, it can stick to form the nucleus of an atom of helium, a variety called helium-3 containing two protons and one neutron. Two of these helium-3 nuclei in turn combine to form one nucleus of helium-4, containing two protons and two neutrons, with the release of two protons—hydrogen nuclei—which go back into the stellar melting pot.

The net effect of this cycle of activity is to convert four protons into one helium-4 nucleus, and to release energy. This is nuclear fusion, the basis of the hydrogen bomb. A star like the Sun, indeed, is the cosmic equivalent of a hydrogen bomb, one which explodes continuously for ten thousand million years. The energy released keeps a star hot in the middle and holds it up against further collapse, for as long as the supply of hydrogen fuel lasts. Ultimately, however, the fuel must run out as all of the hydrogen in the middle is converted into helium. At that point, the star will begin to collapse again, getting hotter still in its heart, with pressure building up until conditions are so extreme that the helium nuclei themselves begin to combine, with three nuclei of helium-4 getting together to make one nucleus of carbon, which contains six protons and six neutrons. Once again, this process releases energy (now at a still higher temperature) and the collapse is halted—until almost all the helium has been converted into carbon. Then, the whole cycle repeats again, with successively heavier elements being built up in the central regions of a massive star as it gets older. This happens quickly for massive stars, and any massive first generation stars formed when the Universe was young have all long since burned out.

The heaviest element that can be made in this way is iron, the most stable element of all. Whereas fusion of lighter elements to make heavier elements releases energy all the way up the ladder to iron, to make the heavier elements it is necessary to put energy in to force the nuclei to combine with one another. This only happens in very massive stars—but when it does happen, it happens in spectacular fashion.

When a very massive star has used up all of its nuclear fuel, and has grown a core of gaseous iron, nuclei pounding against one another at a temperature of tens of millions of degrees, there comes a time when no more energy is being released and it can no longer hold itself up against gravity. This happens when the iron core is about one and a half times the entire mass of our Sun, for a star whose total mass is ten or more times the mass of our Sun. At this point, the iron core collapses very suddenly to a superdense state in which all of the protons and electrons fuse together to make neutrons. The equivalent of the entire mass of our Sun is packed into a ball of neutron matter no bigger than the island of Manhattan. And this collapse releases an enormous amount of gravitational energy, which goes into the outer 90 per cent of the star. In the early phase of the resulting explosion, atomic nuclei are forced together to create the heavy elements, such as lead and uranium; then, split-seconds later, the entire outer part of the star is ripped away and scattered across space. Eventually, the elements created inside the dying star will become part of new gas clouds in space, which will collapse to form stars and planets, like our Solar System. Our Sun is a later generation star, and that is why it contains some elements other than hydrogen and helium, and why it has a retinue of planets made out of heavier elements. We owe our life to the death throes of stars. ■

How helium is formed from hydrogen in a star.

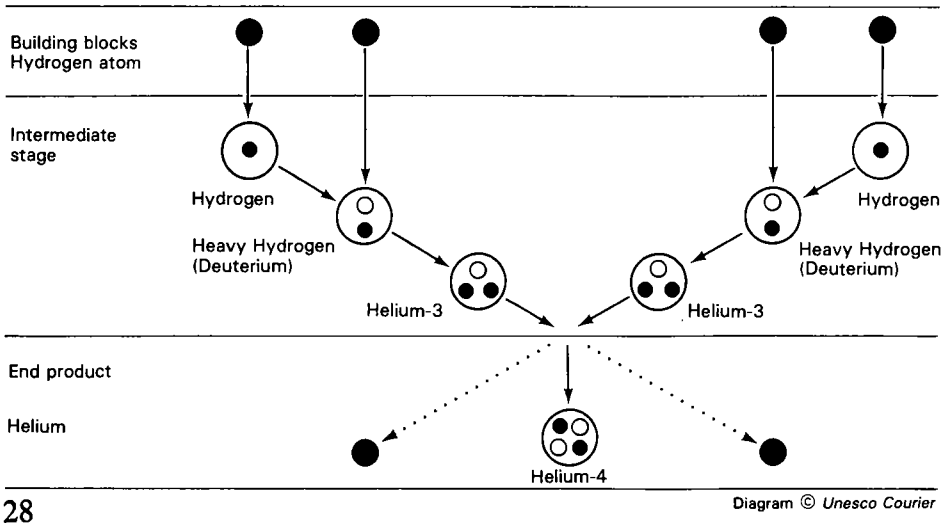
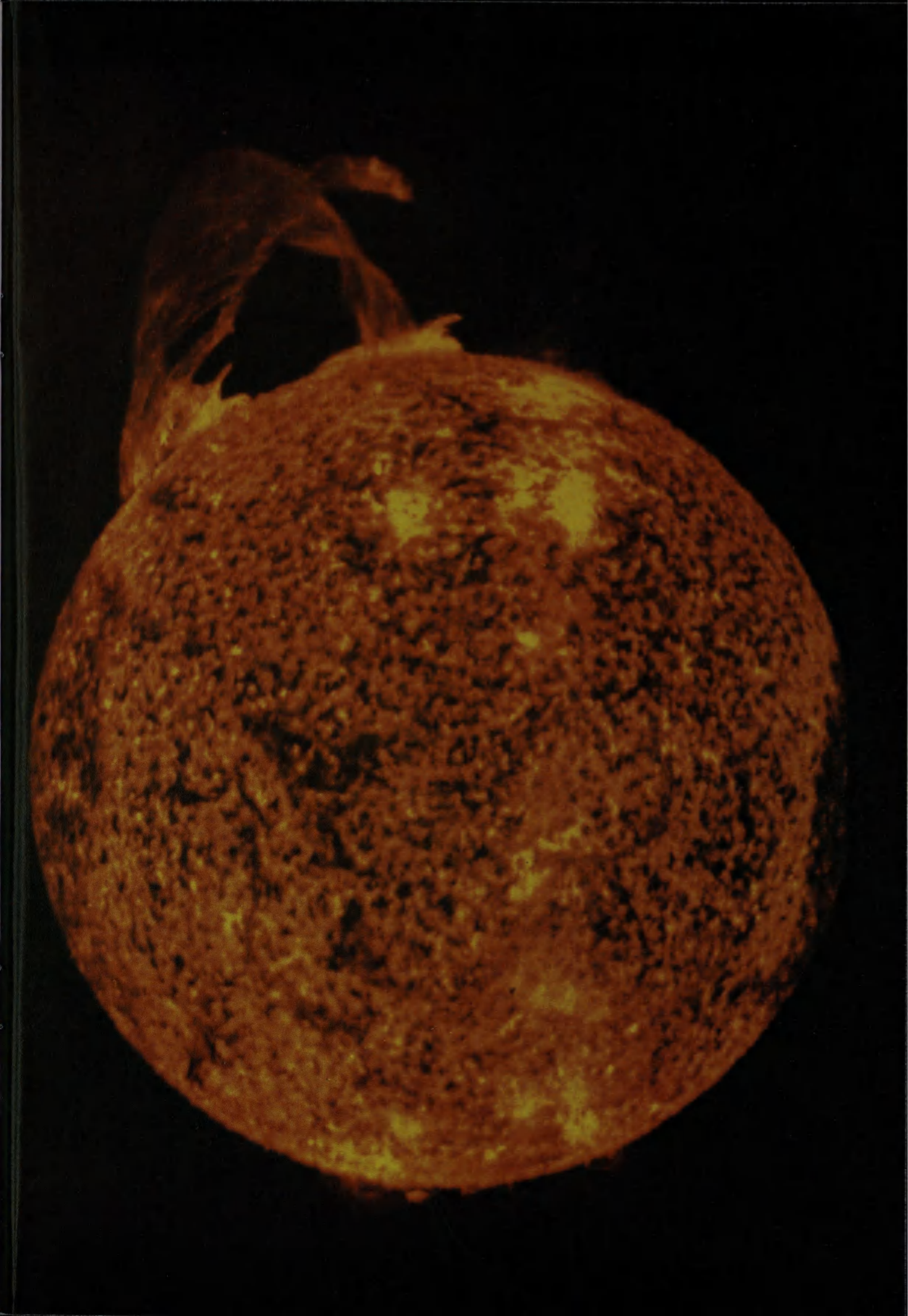


Diagram © *Unesco Courier*

Colour page 29

The Sun, a main-sequence star, is a dense spherical mass of glowing matter 1,392,000 kilometres in diameter. Consisting largely of hydrogen, and with a temperature at its centre of an inconceivable 13 million degrees Centigrade, it is a seething cauldron in which electrons are stripped from their atoms and nuclei collide and fuse in a series of reactions which have the net result of converting hydrogen into helium. The Sun is about half way through its cycle of life as a main-sequence star; in about 5,500 million years it will have burnt up its supply of hydrogen and will die. At the Sun's surface, gases carrying away heat from the interior seethe and bubble, producing flares and prominences that erupt hundreds of thousands of kilometres into space. Photo, taken from Skylab 4, in December 1973, shows a prominence spanning some 586,000 kilometres, one of the most spectacular ever recorded.



The mystery of LIFE

by Carl Sagan

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Colour page 30

Above

This infra-red image of the Milky Way as a glowing iridescent wand is a product of a breakthrough which has enabled astronomers to observe for the first time a universe that had hitherto been invisible and inaccessible to them. It was transmitted in 1983 from an infra-red telescope mounted in the infra-red Astronomical Satellite (IRAS), a 12-month project in which Dutch, US and British astronomers took part. Infra-red waves, which resemble light waves but cannot be seen by the naked eye, pass through the dense clouds of interstellar dust that obscure the starlight whereby astronomers using optical telescopes observe the universe. Infra-red observatories have been built on high mountaintops, but such earthbound observations are difficult because most infra-red radiation is absorbed by water in the earth's atmosphere. An infra-red observatory in space was the answer to the problem, and IRAS has provided a mass of data about star formation which will take years to analyse fully and seems likely to modify many accepted beliefs.

Below

The Pleiades are a dense cluster of stars some 60 million years old, still in the process of formation. Six or seven can be seen by the naked eye and the cluster is commonly known as the Seven Sisters, but photographs reveal that there are several hundred stars in the group.

Photos © IPS, Paris

ALL my life I have wondered about the possibility of life elsewhere. What would it be like? Of what would it be made? All living things on our planet are constructed of organic molecules—complex microscopic architectures in which the carbon atom plays a central role. There was once a time before life, when the earth was barren and utterly desolate. Our world is now overflowing with life. How did it come about? How, in the absence of life, were carbon-based organic molecules made? How did the first living things arise? How did life evolve to produce beings as elaborate and complex as we, able to explore the mystery of our own origins?

And on the countless other planets that may circle other suns, is there life also? Is extraterrestrial life, if it exists, based on the same organic molecules as life on Earth? Do the beings of other worlds look much like life on Earth? Or are they stunningly different—other adaptations to other environments?

In the great dark between the stars there are clouds of gas and dust and organic matter. Dozens of different kinds of organic molecules have been found out there by radio telescopes. The abundance of these molecules suggests that the stuff of life is everywhere.

CARL SAGAN, *of the USA, is director of the Laboratory for Planetary Studies and David Duncan Professor of Astronomy and Space Sciences at Cornell University, Ithaca, New York. A former chairman of the Division for Planetary Sciences of the American Astronomical Society, he played a leading role in the Mariner, Viking and Voyager expeditions to the planets. He is the author, co-author or editor of more than a dozen books including* Intelligent Life in the Universe, The Cosmic Connection, The Dragons of Eden, *and* Broca's Brain, *and in 1978 he was awarded the Pulitzer Prize for literature. This article is extracted from* Cosmos, *a book based on Professor Sagan's major television series which has attracted a worldwide viewing audience of millions throughout the world.*

Perhaps the origin and evolution of life is, given enough time, a cosmic inevitability. On some of the thousands of millions of planets in the Milky Way Galaxy, life may never arise. On others it may arise and die out, or never evolve beyond its simplest forms. And on some small fraction of worlds there may develop intelligences and civilizations more advanced than our own.

Occasionally someone remarks on what a lucky coincidence it is that the Earth is perfectly suitable for life—moderate temperatures, liquid water, oxygen atmosphere, and so on. But this is, at least in part, a confusion of cause and effect. We earthlings are supremely well adapted to the environment of the Earth because we grew up here. Those earlier forms of life that were not well adapted died. We are descended from the organisms that did well. Organisms that evolve on a quite different world will doubtless sing its praises too.

All life on Earth is closely related. We have a common organic chemistry and a common evolutionary heritage. As a result, our biologists are profoundly limited. They study only a single kind of biology, one lonely theme in the music of life. Is this faint and reedy tune the only voice for thousands of light-years? Or is there a kind of cosmic fugue, with themes and counterpoints, dissonances and harmonies, a thousand million different voices playing the life music of the Galaxy?

What happened here on Earth may be more or less typical of the evolution of life on many worlds; but in such details as the chemistry of proteins or the neurology of brains, the story of life on Earth may be unique in all the Milky Way Galaxy.

The Earth condensed out of interstellar gas and dust some 4.6 thou- ▶

▶sand million years ago. We know from the fossil record that the origin of life happened soon after, perhaps around four thousand million years ago, in the ponds and oceans of the primitive Earth.

The first living things were not anything so complicated as a one-celled organism, already a highly sophisticated form of life. The first stirrings were much more humble. In those early days, lightning and ultraviolet light from the Sun were breaking apart the simple hydrogen-rich molecules of the primitive atmosphere, the fragments spontaneously recombining into more and more complex molecules. The products of this early chemistry were dissolved in the oceans, forming a kind of organic soup of gradually increasing complexity, until one day, quite by accident, a molecule arose that was able to make crude copies of itself, using as building blocks other molecules in the soup.

This was the earliest ancestor of deoxyribonucleic acid (DNA), the master molecule of life on Earth. It is shaped like a ladder twisted into a helix, the rungs available in four different molecular parts, which constitute the four letters of the genetic code. These rungs, called nucleotides, spell out the hereditary instructions for making a given organism.

Every lifeform on Earth has a different set of instructions, written out in essentially the same language. The reason organisms are different is the differences in their nucleic instructions. A mutation is a change in a nucleotide, copied in the next generation, which breeds true. Since mutations are random nucleotide changes, most of them are harmful or lethal, coding into existence non-functional enzymes. It is a long wait before a mutation makes an organism work better. And yet it is that improbable event, a small beneficial mutation in a nucleotide a ten-millionth of a centimetre across, that makes evolution work.

Four thousand million years ago, the Earth was a molecular Garden of Eden. There were as yet no predators. Some molecules reproduced themselves inefficiently, competing for building blocks, and left crude copies of themselves. With reproduction, mutation and the selective elimination of the least efficient varieties, evolution was well under way, even at the molecular level.

As time went on they got better at reproducing. Molecules with specialized functions eventually joined together, making a kind of molecular collectivity—the first cell.

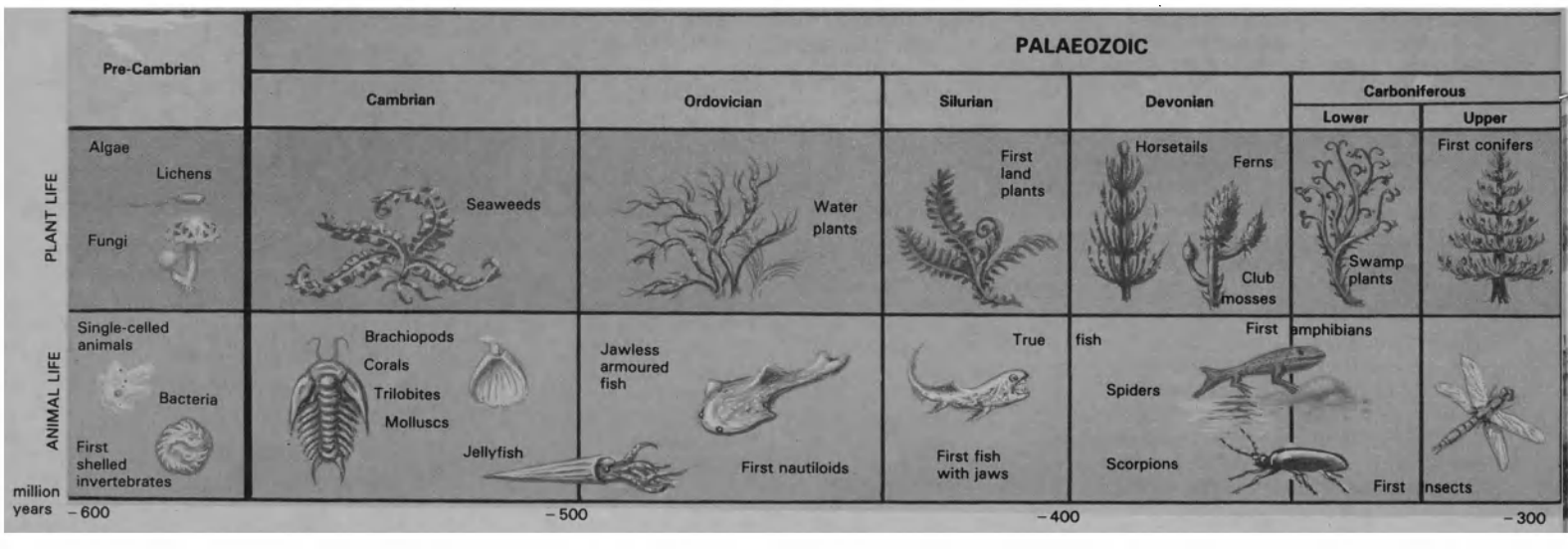
By three thousand million years ago, a number of one-celled plants had joined together, perhaps because a mutation prevented a single cell from separating after splitting in two. The first multi-cellular organisms had evolved. Every cell of your body is a kind of commune, with once free-living parts all banded together for the common good. And you are made of a hundred million million cells. We are, each of us, a multitude.

Sex seems to have been invented around two thousand million years ago. Before then, new varieties of organisms could arise only from the accumulation of random mutations—the selection of changes, letter by letter, in the genetic instructions. Evolution must have been agonizingly slow. With the invention of sex, two organisms could exchange whole paragraphs, pages and books of their DNA code, producing new varieties ready for the sieve of selection.

By one thousand million years ago, plants, working co-operatively, had made a stunning change in the environ-

Above, against a backdrop of stars, this ancient Chinese painting portrays an intertwined double helix representing the interaction of opposites, the* Yin *and the* Yang, *which in Chinese cosmology resulted in the Creation. Right, demonstration model of the DNA (deoxyribonucleic acid) double helix, the master molecule of life at the heart of every living cell. Shaped like a ladder twisted into a spiral, DNA carries the hereditary set of instructions which determine whether a living organism will become, for example, a centipede, a whale, a human being or a tree.

The span



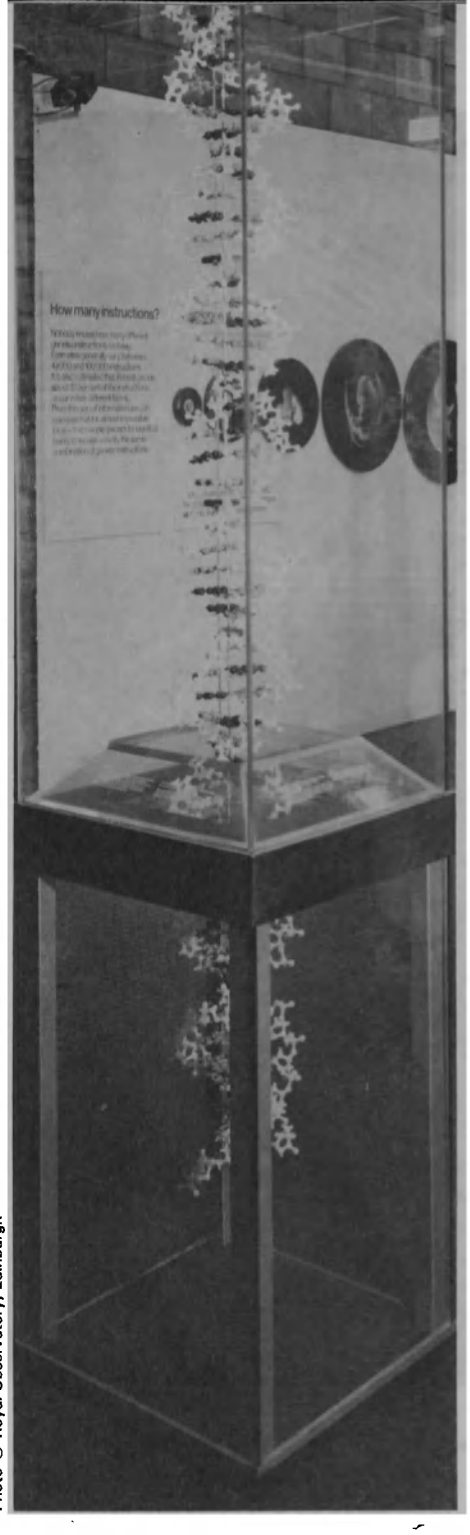


Photo © Royal Observatory, Edinburgh

ment of the Earth. Green plants generate molecular oxygen. Since the oceans were by now filled with simple green plants, oxygen was becoming a major constituent of the Earth's atmosphere, altering it irreversibly from its original hydrogen-rich character and ending the epoch of Earth history when the stuff of life was made by non-biological processes. But oxygen tends to make organic molecules fall to pieces. Despite our fondness for it, it is fundamentally a poison for unprotected organic matter.

The transition to an oxidising atmosphere posed a supreme crisis in the history of life, and a great many organisms, unable to cope with oxygen, perished. A few primitive forms, such as the botulism and tetanus bacilli, manage to survive even today in oxygen-free environments. The nitrogen in the Earth's atmosphere is much more chemically inert and therefore much more benign than oxygen. But it too is biologically sustained. Thus ninety-nine per cent of the Earth's atmosphere is of biological origin. The sky is made of life.

For most of the four thousand million years since the origin of life, the dominant organisms were microscopic blue-green algae, which covered and filled the oceans. Then, some six hundred million years ago, the monopolizing grip of the algae was broken and an enormous proliferation of new lifeforms emerged, an event called the Cambrian explosion.

Life had arisen almost immediately after the origin of the Earth, which suggests that life may be an inevitable chemical process on an Earth-like planet. But life did not evolve much beyond blue-green algae for three thousand million years, which suggests that large lifeforms with specialized organs are hard to evolve, harder even than the origin of life. Perhaps there are many other planets that today have abundant microbes but no big beasts and vegetables.

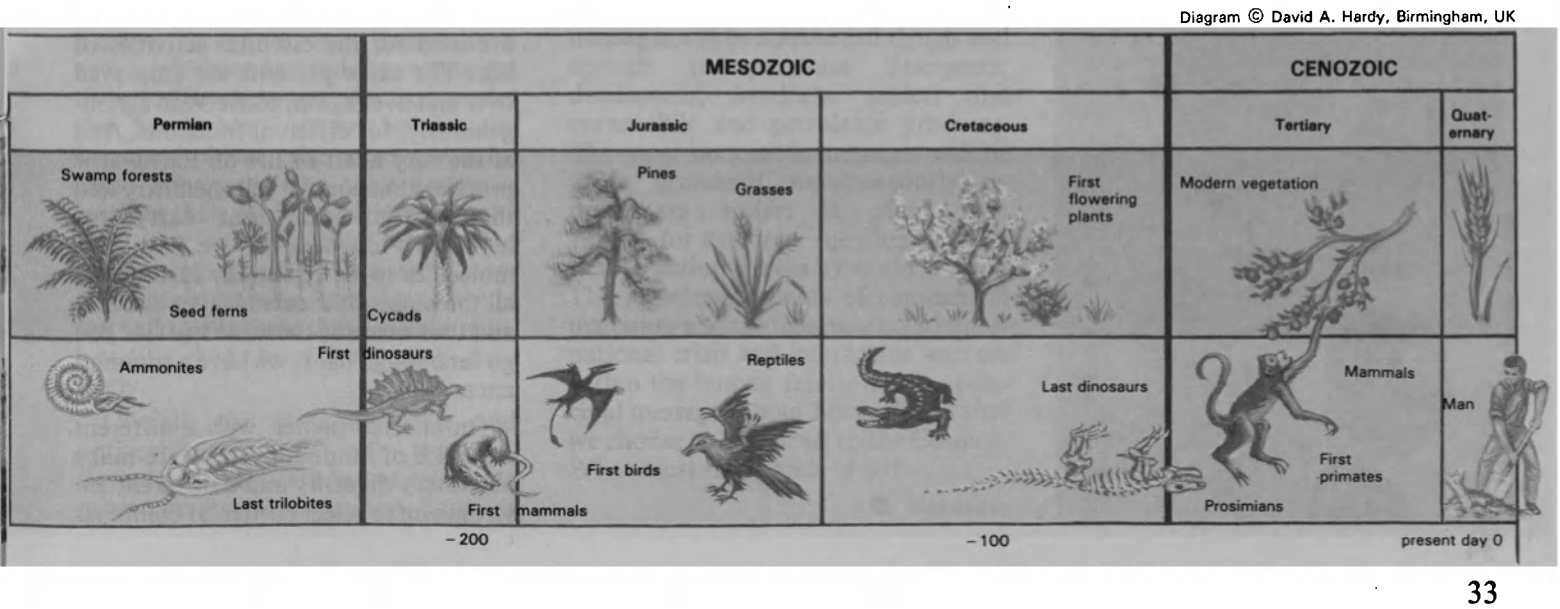
Soon after the Cambrian explosion, the oceans teemed with many different forms of life. By five hundred million years ago there were vast herds of trilobites, beautifully constructed animals, a little like large insects. They stored crystals in their eyes to detect polarized light. But there are no trilobites alive today; there have been none for two hundred million years. The Earth used to be inhabited by plants and animals of which there is today no living trace. And of course every species now on the planet once did not exist. There is no hint in the old rock of animals like us. Species appear, abide more or less briefly, and then flicker out.

Before the Cambrian explosion species seem to have succeeded one another rather slowly. But after the Cambrian explosion exquisite new adaptations followed one another with comparatively breathtaking speed.

In rapid succession, the first fish and the first vertebrates appeared; plants, previously restricted to the oceans, began the colonization of the land; the first insect evolved, and its descendants became the pioneers in the colonization of the land by animals; winged insects arose together with the amphibians, creatures something like the lungfish, able to survive both on land and in the water; the first trees and the first reptiles appeared; the dinosaurs evolved; the mammals emerged, and then the first birds; the first flowers appeared; the dinosaurs became extinct; the earliest cetaceans, ancestors to the dolphins and whales arose, and in the same period the primates—the ancestors of the monkeys, the apes and the humans. Less than ten million years ▶

of life

Diagram © David A. Hardy, Birmingham, UK



"If there are intelligent beings on the planets of fairly nearby stars, could they know about us? Today there is a vast international radio, television and radar communications traffic. At some radio frequencies the Earth has become by far the brightest object, the most powerful radio source, in the solar system—brighter than Jupiter, brighter than the Sun. An extraterrestrial civilization monitoring the radio emission from Earth and receiving such signals could not fail to conclude that something interesting had been happening here lately."
Right, Strahlenlinien *(Radiating), 1927. Oil on canvas by Wassily Kandinsky.*

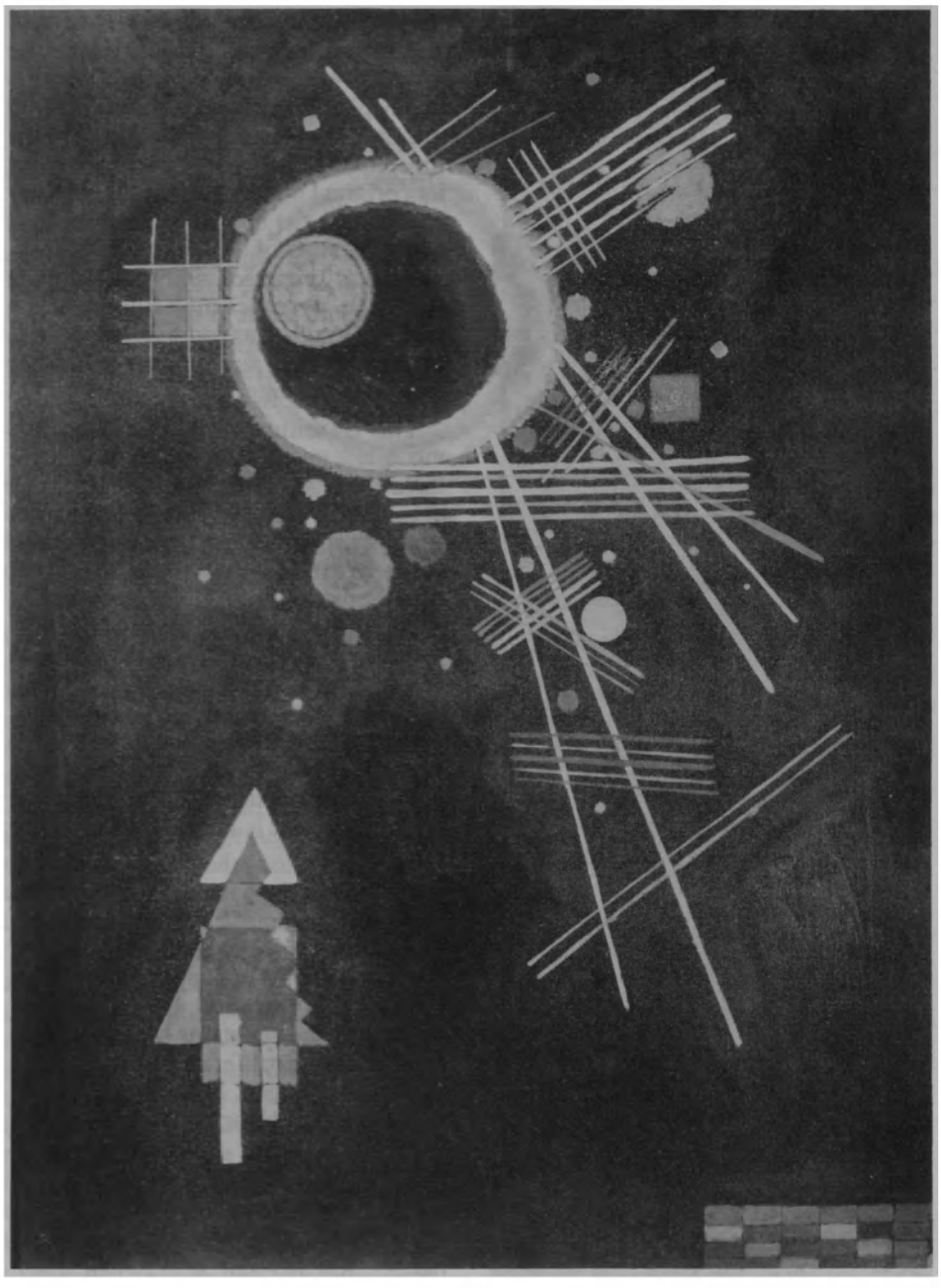


Photo © Boymans van Beuningen Museum, Rotterdam

Photo Ciccione © Rapho, Paris

Life has existed on earth for four thousand million years. For about half of that time organisms reproduced themselves by cell division which only rarely produces new life forms by accidental mutation. The emergence of two sexes and sexual reproduction, which made possible the exchange of huge amounts of genetic information, was responsible for the dazzling variety of life forms and species in the world today. Sex as a biological mechanism was invented by the green algae. Below, cells of the green alga Spirogyra *in the process of conjugation.*

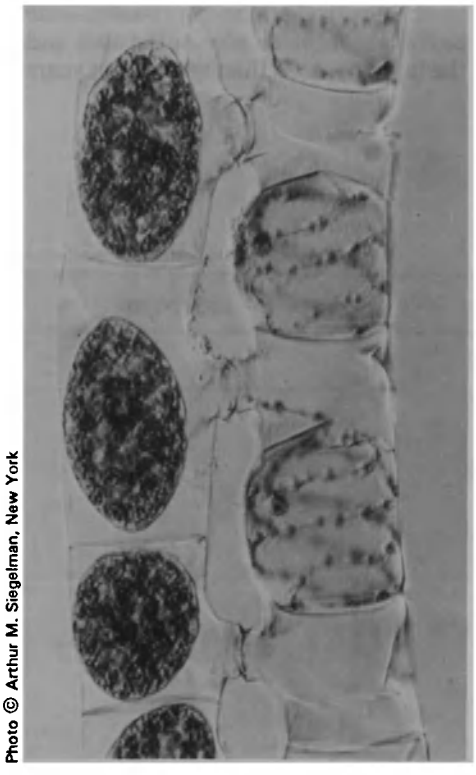
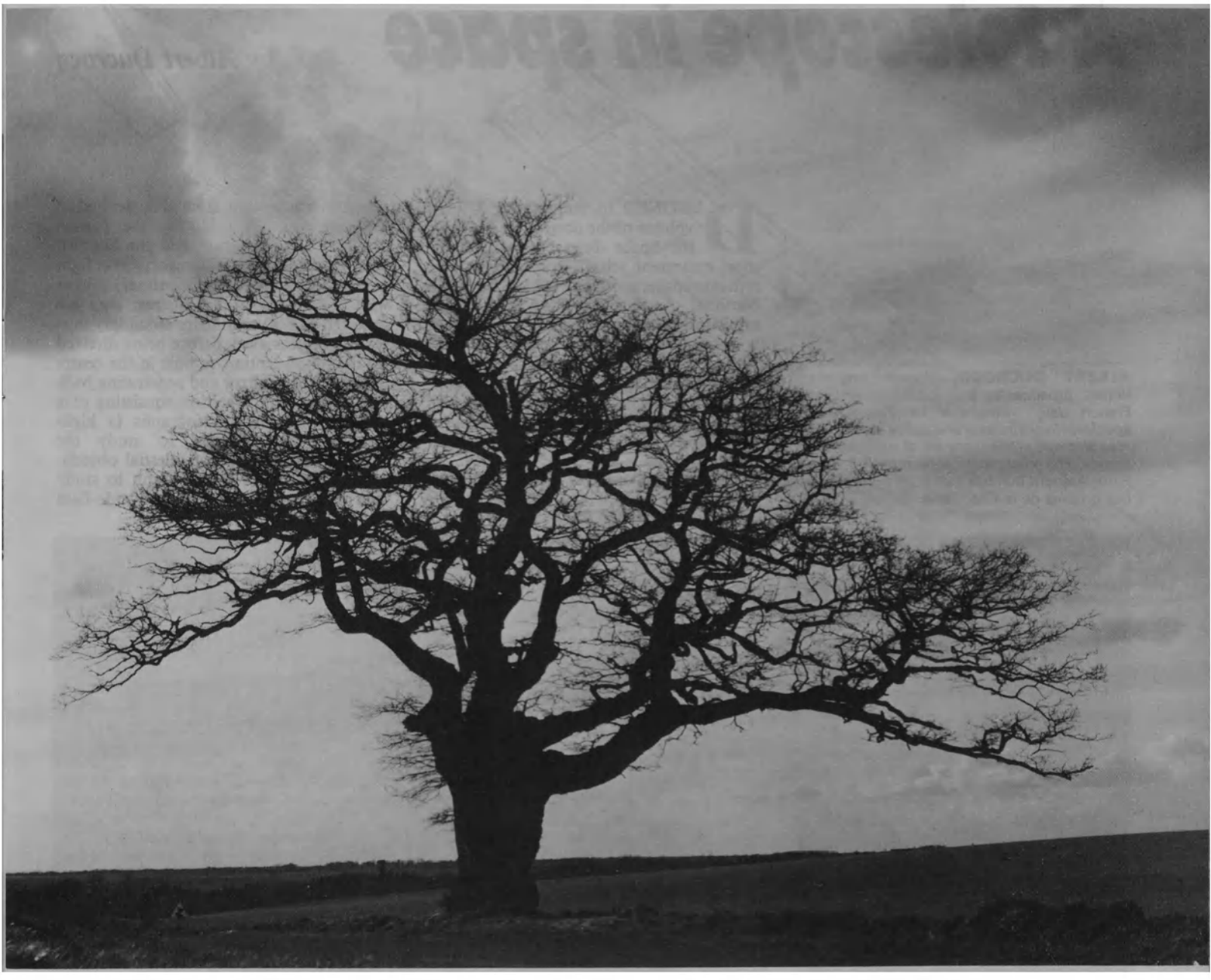


Photo © Arthur M. Siegelman, New York

▶ago, the first creatures who closely resembled human beings evolved, accompanied by a spectacular increase in brain size. And then, only a few million years ago, the first true humans emerged.

There are tens of thousands of millions of known kinds of organic molecules. Yet only about fifty of them are used for the essential activities of life. The same patterns are employed over and over again, conservatively, ingeniously, for different functions. And at the very heart of life on Earth—the proteins that control cell chemistry and the nucleic acids that carry the hereditary instructions—we find these molecules to be essentially identical in all the plants and animals. An oak tree and I are made of the same stuff. If you go far enough back, we have a common ancestor.

On another planet, with a different sequence of random processes to make hereditary diversity and a different environment to select particular combina-



tions of genes, the chances of finding beings who are physically very similar to us is, I believe, near zero. The chances of finding another form of intelligence is not.

If there are intelligent beings on the planets of fairly nearby stars, could they know about us? One way would be to listen with large radio telescopes. Today there is a vast international radio, television and radar communications traffic. At some radio frequencies the Earth has become by far the brightest object, the most powerful radio source, in the solar system—brighter than Jupiter, brighter than the Sun. An extraterrestrial civilization monitoring the radio emission from Earth and receiving such signals could not fail to conclude that something interesting had been happening here lately.

Overall, the most pervasive and noticeable source of radio transmissions from the Earth is our television programming. Because the Earth is turning some television stations will appear at one horizon of the Earth while others will disappear over the other. There will be a confused jumble of programmes. Even these might be sorted out and pieced together by an advanced civilization on a planet of a nearby star.

The most frequently repeated messages will be station call signals and appeals to purchase detergents, deodorants, headache tablets and automobile and petroleum products. The most noticeable messages will be those broadcast simultaneously by many transmitters in many time zones—for example, speeches in times of international crisis by world leaders. The mindless contents of commercial television and the integuments of international crisis and internecine warfare within the human family are the principal messages about life on Earth that we choose to broadcast to the Cosmos. What must they think of us?

■ **Carl Sagan**

"Trees are great and beautiful machines, powered by sunlight, taking in water from the ground and carbon dioxide from the air, converting these materials into food for their use and ours... There are tens of billions of known kinds of organic molecules, yet only fifty of them are used for the essential activities of life. The same patterns are employed over and over again, conservatively, ingeniously for different functions. And at the very heart of life on earth... we find these molecules to be essentially identical in all the plants and animals. A tree and I are made of the same stuff."

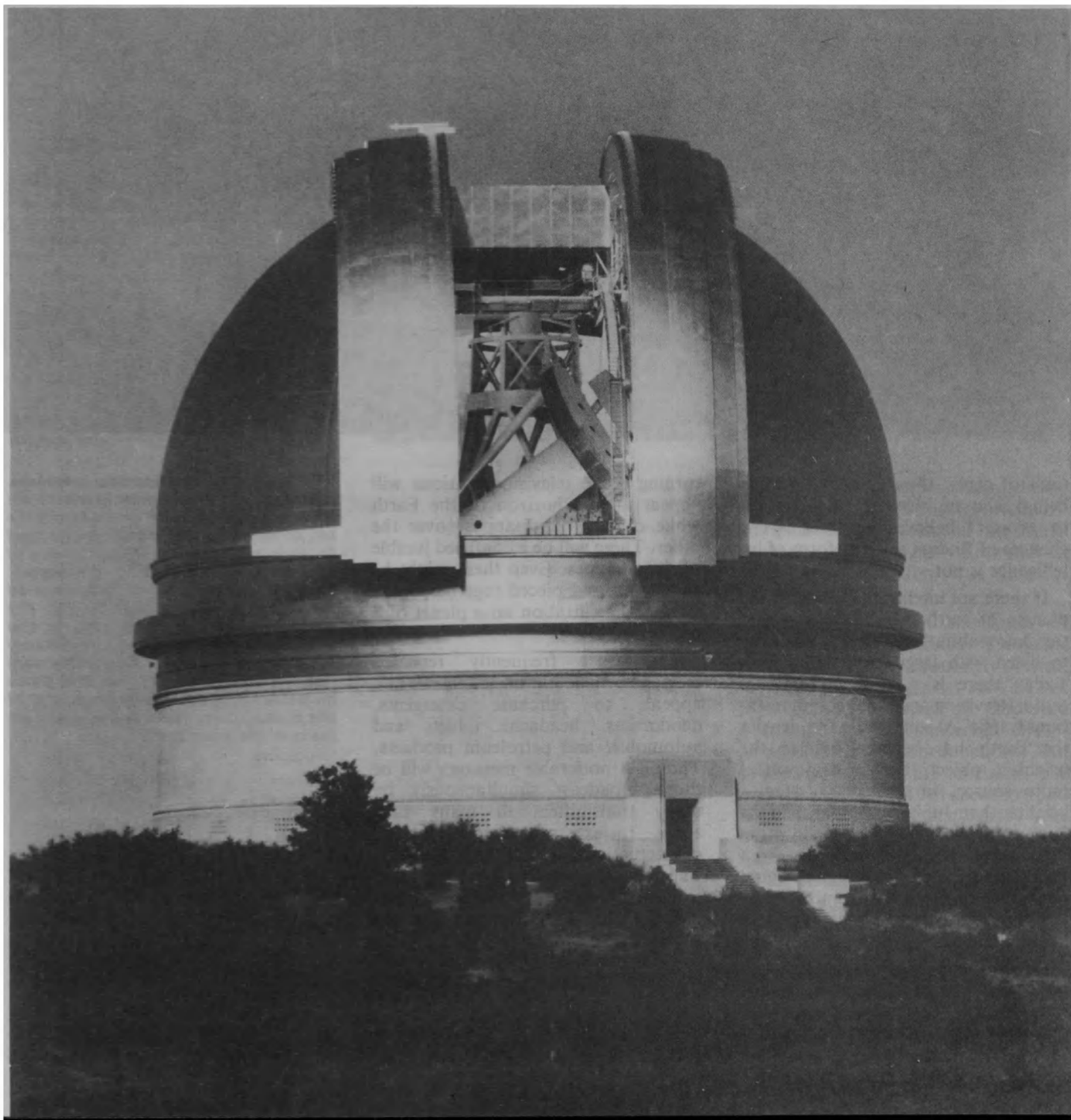
A telescope in space

by Albert Ducrocq

ALBERT DUCROCQ, *French engineer, writer, broadcaster and journalist with the French daily newspaper* Le Figaro, *is a specialist in cosmology and space matters and was also one of the pioneers of cybernetics in France. The most recent of his many books,* Le Futur Aujourd'hui, *has just been published by* Les presses de la Cité, *Paris.*

DESTINED to multiply by 350 the volume of the observable universe, the Space Telescope will be the most important scientific instrument ever sent into space, according to NASA (the US National Aeronautical and Space Administration) administrator James Beggs. It is scheduled to be put into orbit 550 kilometres above the earth sometime in 1986 by the space shuttle, to the dimensions of which it has been tailored (when folded it will be 13.1 metres long with a diameter of 4.27 metres).

The key component of the 11-ton instrument will be a telescope only slightly different in conception from that devised in the seventeenth century by the French physicist N. Cassegrain and the Scottish mathematician James Gregory: the light rays strike a hyperboloidal primary mirror with a diameter of 2.4 metres; they are reflected to a 30-centimetre secondary mirror five metres away before being directed through a 60-centimetre hole in the centre of the primary mirror and penetrating back into an instrument section consisting of a photometer, two spectrographs (a high-resolution spectrograph to study the chemical composition of celestial objects, and a faint-object spectrograph to study their speed), and two cameras (a wide-field



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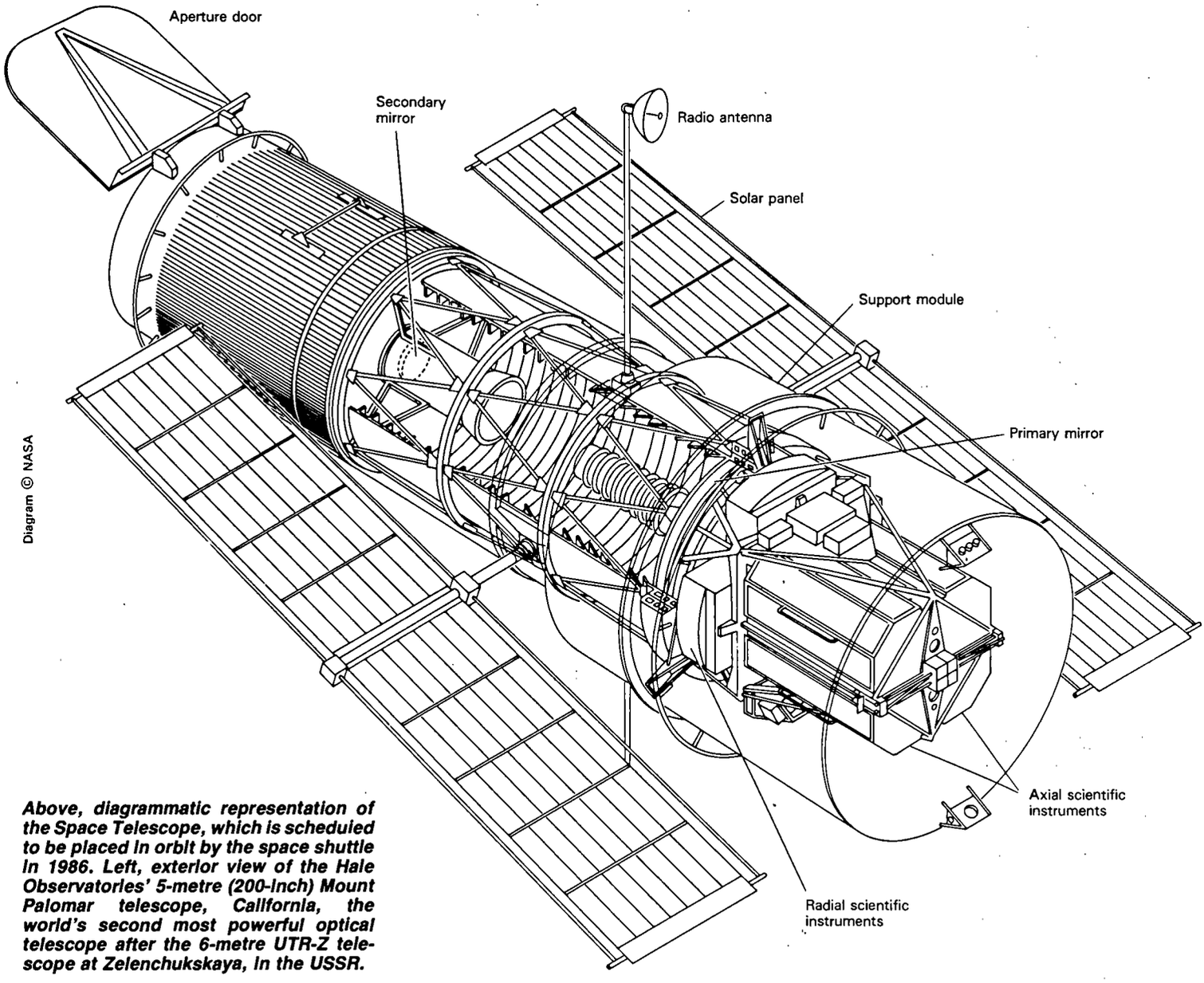

Diagram © NASA

Above, diagrammatic representation of the Space Telescope, which is scheduled to be placed in orbit by the space shuttle in 1986. Left, exterior view of the Hale Observatories' 5-metre (200-inch) Mount Palomar telescope, California, the world's second most powerful optical telescope after the 6-metre UTR-Z telescope at Zelenchukskaya, in the USSR.

camera sensitive to wavelengths ranging from the infra-red to the ultraviolet, and an ultrasensitive faint-object camera with a field forty times smaller).

The great telescopes of Mount Palomar and Zelenchukskaya have 5- and 6-metre apertures respectively, but the Space Telescope should produce a far higher performance, if only because of the extraordinary care with which its mirror has been made from fused silica glass with a very low coefficient of thermal expansion, fixed on a honeycomb structure. Construction of the 829-kilo mirror began in October 1977 and it was delivered in December 1978. Computer-controlled polishing was so precise that the overall deviation of the reflecting surfaces from their ideal contour is no more than 10 nanometres*; the same precision was observed in the application of an 80-nanometre-thick coating of aluminium and a protective layer of magnesium floride 25 nanometres thick.

Observations of the sky from the earth are impeded by the earth's atmosphere, which is always turbulent (even when it is supposedly calm the stars "twinkle" in a conventional telescope) and is slightly luminous because it diffuses all kinds of radiation. In space these disadvantages do not exist.

How will the Space Telescope be controlled? Its rear section is a "support module" which will act as a platform and is equipped with a stellar sensor and a gyroscope with a fine-guidance precision of .007 arc-seconds. It will be possible to hold the optical axis on to a point 30 kilometres away to within 1 mm for a very long period. For some programmes the optical axis will be held steady for up to ten hours which should make it possible to observe stars of the 29th magnitude.

The instrument will not take photographs. A solid-state CCD (charge coupled device) system has been chosen instead of film. There will be four microelectronic silicon chips, each one a square measuring 1.2 cm, with 800 individual picture elements (pixels) on each side, so that each chip has a total of 640,000 pixels. The sensitivity will be 50 times that of film.

A retransmission system in the support module will relay information to the earth by means of the NASA Tracking and Data Relay Satellite System at a rate of a million bits of information per second. The energy distribution system will also be housed in the support module. The current will be provided by two solar panels, one on each side of the Telescope. Each measures 2.3 metres by 11.8 metres. The panels are expected to produce 2.4 kW.

Astronomers will adjust the instruments and carry out experiments using scientific equipment installed in eight boxes mounted behind the primary mirror. There could be no question of their being in direct physical contact with the Space Telescope while it is in operation. In view of the degree of precision that is being sought, human heartbeats alone would make the apparatus vibrate. In the normal course of events, operations will be carried out automatically according to procedures controlled from earth.

From time to time, perhaps every two years, the Space Telescope will be visited by astronauts who will check the equipment and make any necessary adjustments.

The Space Telescope will be the spearhead of astronomy until the end of the century. After five years' service it is planned that the Telescope will be returned to earth in the shuttle to be modernized and equipped with the new and more compact CCDs which will have been developed by that time.

■ **Albert Ducrocq**

** 1 nanometre = 1 millionth of a millimetre.*

Glossary

BARYONS. A collective name for neutrons and protons.

BIG BANG THEORY. The theory that the Universe has evolved as the result of the explosion of an agglomeration of superdense matter. The expansion of the Universe is thought to be the result of this explosion, with galaxies flying apart like fragments of an exploding bomb (see article page 5).

BLACK HOLE. A hypothetical region of space having a gravitational pull so great that no matter or radiation, not even light, can escape from it. Such regions are believed to form when a massive star collapses, having used up all its nuclear fuel (see page 22).

CERN. Abbreviation for *Conseil Européen pour la Recherche Nucléaire* (European Organization for Nuclear Research), established in Geneva. Switzerland, in 1952.

ELECTRON. A negatively charged particle that is a constituent of all atoms.

GALAXY. A large system of stars, dust and gas. The Milky Way, of which our solar system is a part, is a spiral galaxy.

KELVIN. (Symbol: K). The Kelvin temperature scale, named after the British physicist William Thomson (Lord Kelvin) takes absolute zero as its starting point, as compared with the Celsius (Centigrade) scale on which absolute zero is minus 273.15 degrees. The units of interval of the Kelvin and Celsius scales are identical, so a temperature expressed in degrees Celsius is always equal to a temperature in Kelvins less 273.15 degrees.

LIGHT-YEAR. The distance travelled by light in one year $= 9.460 \times 10^{15}$ metres, roughly ten million million kilometres.

LOCAL GROUP. A cluster of about twenty known galaxies including the Milky Way.

MILKY WAY. A spiral galaxy of some thousands of millions of stars, including our own Sun.

NEBULA. A region of dust and gas in a galaxy. Sometimes used in the past to indicate a galaxy.

NEUTRON. An elementary particle that is a constituent of all atomic nuclei except that of normal hydrogen.

NEUTRON STAR. A star at the end of its evolutionary process that has become highly compressed by gravitational forces.

POSITRON. The positively charged anti-particle corresponding to the electron.

PROTON. A positively charged elementary particle. The proton is a constituent of all atomic nuclei.

PULSAR. A rotating neutron star that emits short regular pulses of radiation.

QUARK. A hypothetical sub-atomic particle. Baryons are thought to consist of three quarks bound together.

QUASAR. Quasi stellar radio sources. Extra-galactic sources of high energy electromagnetic radiation.

RED SHIFT. A displacement towards the red end of the spectrum of the light waves from stars or other celestial objects. The implication of this displacement is that the objects are receding. Red shift is the chief evidence for the expansion of the Universe (see page 16).

STEADY STATE THEORY. The theory that the Universe has always existed in a steady state and that the expansion of the Universe is compensated for by the continuous creation of matter.

SUPERNOVA. An exploding star. At the end of its phase as a Red Giant, a heavy star explodes as a supernova shining briefly as brightly as a thousand million Suns.

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General editor Joseph Rotblat
Co-published with Taylor & Francis Ltd., London, who have exclusive sales rights in the United Kingdom.
1982. 323 pp. ISBN 92-3-102021-8.
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- Role of scientists in the arms race
- Movements of scientists against the arms race
- Social responsibility of scientists
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- Role of the United Nations

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1983. 269 pp. ISBN 92-3-102119-2.
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Edited by Marek Thee, Director, International Peace Research Institute, Oslo
1982. First published 1981. 446 pp.
ISBN 92-3-101920-1. 100 French francs

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